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A Distributed Computing Network for Real-Time Systems

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PREFACE

This document is based on the thesis of the author, which was submitted to the Department of Computer Science, University of Rhode Island, in partial fulfillment of the requirements for the degree of Master of Science.

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Partial interconnection, ring, and global bus topologies are examined in this document for use in a real-time distributed computing network. Message lengths and capacity allocation strategies for network links are evaluated in determining system performance based on average message delay. The data suggest a network topology for the application under study.

Processor delays at each of the nine nodes in the network are

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20. ABSTRACT (Cont'd)

introduced in a simulation model of a global bus network. Thus, link traffic and processor delays are utilized with message arrival rate, network bandwidth, and processor capacity parameters to arrive at a satisfactory computer system network for a real-time application.

A methodology is developed whereby software requirements are determined in terms of the number of instructions executed. The desired system response time is established and software and hardware specifications may then be defined.

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1.0 INTRODUCTION

Many real-time computing systems continue to utilize the centralized computer system architecture concept where several subsystems are integrated to function under an executive program in a mainframe digital computer. While this approach had certain advantages years ago when hardware costs were high compared with software costs, the concept has proven to have many disadvantages. Now that hardware costs have been reduced relative to software costs, a potential solution is to develop a distributed computing system design where the system functions and data base are partitioned into several minicomputers or microcomputers connected in a system network and under the control of a distributed operating system.

Communication networks may conveniently be categorized as circuit switching, message switching and packet switching (Kleinrock 1976).

A circuit-switching network provides service by setting up the complete path of connected channels from the source to the destination. After the path is established, a return signal informs the source that data transmission may proceed and all channels are used simultaneously. When the message has been transmitted over the path, the source node releases the circuit and the channels become available for use by other paths.

In a message-switching communications network, only one channel is used at a time for a given transmission. The message first travels from its source node to the next node in its path and when the entire message is received at the node then the next step in its journey is selected. If this selected channel is busy, the message waits in a queue and when the channel becomes free, transmission of the message continues.

Packet switching is similar to message switching except that the messages are divided into smaller pieces called packets that have a maximum length. The packets are numbered and addressed and travel through the net in a packet-switched (store and forward) manner. Many packets of the same message may be in transmission simultaneously, thereby reducing the transmision delay.

The communication networks examined in this paper are classified as message-switching networks.

Regarding the composition of a communication network, Kleinrock (1976) relates that it is made up of (1) the physical network, consisting of the switching computers and the communication channels; (2) the flow consisting of messages (described by their origin, destination, origination time, length, and priority class) that move through the network in a store and forward fashion; and (3) the set of operating rules for handling the flow of this message traffic.

A number of design variables are involved in the synthesis of these networks including the message routing procedure, the flow control procedure, the channel capacity assignment, the priority queueing discipline and the topological configuration. A fixed routing procedure is defined as one in which a message's path through the network is uniquely determined from only its origin and destination. When more than one path is possible, the procedure is called an alternate routing procedure. If a routing algorithm bases its decisions on some measure of the observed traffic flow, it is called a dynamic or adaptive routing procedure.

The networks investigated in this paper contain the fixed routing procedure which is established during the design of each network.

The task of controlling the amount of traffic permitted to enter the network is handled by the flow control procedure. The procedure prevents congestion by regulating the entry of trafffic from the processing elements to the communication interface elements and network channels. Local flow control which occurs at each node is a result of the limited buffer space available. Whenever this buffer space is used up, a node has to stop further output to the network channels. Thus, messages may experience an admission delay which contributes to the total delay similar to the queuing delay in the output queues.

Another type of control is called global flow control, which is designed to stop further input to the communication network before all the buffer space in the net is occupied. The flow procedure is intended to prevent a lockup in the network.

The processing capacity in each node has a direct effect on the input of messages to the communication net. The processor and resident software must be capable of generating the messages at a rate consistent with the network requirements. If the node has an insufficient capacity, then the traffic entering the network, γ_{jk} where j is the source node and k is the destination node, in messages per second would not meet the system requirements. An over-processing capability at the node, while meeting the system requirements, would not be a cost-effective design. Thus, the processor and software design for each node must be consistent with the requirements at the particular node.

The topological configuration of the communication network has a significant effect on the network behavior as will be shown later in this paper. Considerations such as network reliability are used in determining the appropriate topology. The queuing discipline that governs the order of service for the many channel queues must also be determined.

After the topology is chosen a capacity assignment must be made to each channel. Schwartz (1977) states that the network requires the best allocation of capacity, link by link, in the sense of minimizing average message time delay. Capacity assignments are dependent upon the routing strategies adopted. Three capacity assignment strategies are examined in this paper:

1. An equal assignment strategy in which the total capacity C is simply divided equally among all the links.

2. A proportional assignment strategy in which C_i, the capacity assigned to link i, is proportional to the traffic demand, λ_i.

3. An optimum capacity assignment strategy in the sense of minimizing the average time delay throughout the network. This is also called the square root assignment strategy as C_i has a term proportional to $\sqrt{\lambda_i}$.

Once a message enters the network, it will eventually be transmitted over a channel; however, if the channel is in use when the message requires this service, then the message must join a queue and wait. The service or transmission time for a given message is the message length (in bits) divided by the capacity of the channel (in bits per second). This procedure occurs at each channel until the message reaches its destination. The total time spent in the network is referred to as message delay (or network delay).

In this paper several network topologies which are considered as candidates for a distributed real-time computing system are examined. A functional system is partitioned into several nodes and the network traffic requirements compiled for selected network topologies. Processing requirements for each node are determined based on the software functional performance necessary.

The average delay time of messages transmitted in a network is of prime interest in the selection of a processor network topology and bandwidth capacity for the channels. Message delay times for each network link (or channel) are determined by analytical methods for each topology considered. This information is used in determining a network topology which provides the minimum message delay for the application under study.

A simulation of the entire network is developed in order to introduce processor delays as these delays are not included in existing network analytical methods. The objective of the simulation experiments is to arrive at a system design which is consistent with the functional software requirements.

The methodology developed in this paper permits the determination of software requirements, in terms of the number of instructions executed, to be accomplished as an initial step in the system design process. The desired system response time is then established and software and hardware specifications may then be defined. A case study serves to illustrate the methodology.

2.0 NETWORK TOPOLOGIES

An examination of computer communication networks reveals there are several alternatives for a distributed computing system. Included in this grouping and identified by the topological characteristics are the ring (or loop), interconnection, global bus and star networks.

The features of a network that distinguish its architecture include its topology, node composition, size and network control techniques. Andersen and Jensen (1975) have provided a comprehensive taxonomy for systems of interconnected computers and those topologies considered as candiates for the system under study will be addressed.

In the star topology, communications from one node to another always pass through the "hub node" which may be a computer or other switching mechanism. The interconnected topology may have nodes connected to one another to the point where each node is connected to every other node. In a ring topology every node is connected to two other nodes of the network. The global bus network has each node interconnected by a common bus.

Network composition may be considered either homogeneous or heterogeneous depending upon the similarity of the switching nodes and attached processors.

The size of a network is usually determined by the number of nodes or processors associated with the system.

Network control functions include establishing the initial connection, flow control, routing, monitoring and measurement. The initial connection can be centralized at one processing element in the network or by allowing the interfaces to the network of the involved processes to be responsible. The traffic flow control between switching nodes will usually be controlled by ordinary line procedures. Routing must be handled by communications software if the message can traverse more than one path in the network. Monitoring and measurement of the network performance can be accomplished by hardware and software distributed in the computer communications network. Network configurations have attributes which make them satisfactory for one application and less desirable for another. Characteristics which aid in this determination include speed, fault tolerance, flexibility and ease of use. The significant factors of each of the network topologies are discussed in the following paragraphs.

2.1 RING NETWORK

Ring architectures as shown in Figures 2-1 consist of a number of individual processing elements (PEs), with each element connected to two neighboring elements. Hereafter, processing elements are referred to as PE's. The traffic flow in a loop could, in principle,

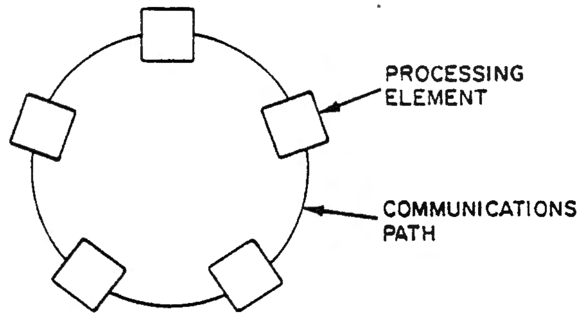


Figure 2-1. Ring Network Topology

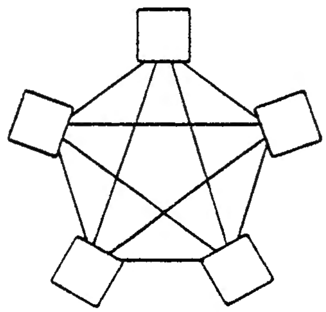


Figure 2-2. Complete Interconnection Network Topology

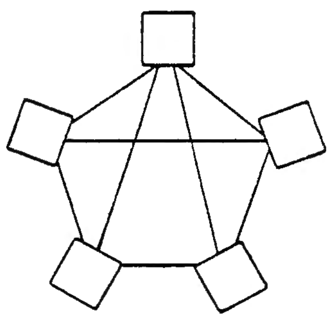


Figure 2-3. Partial Interconnection Network Topology

be in both directions; however, the complexity of bidirectional traffic has made it necessary to have only unidirectional traffic. In a ring network, one neighboring element of a PE may be regarded as a source neighbor and another regarded as a destination neighbor. Messages circulate around a ring from source PE to destination PE with intermediate PEs acting as relay or buffer units. Ring networks allow one or more messages to circulate simultaneously and the messages may be of fixed or variable length.

The ring architecture accepts change easily as an additional PE may be inserted in the ring with the addition of a single communication path and the traffic flow is usually not altered significantly by an addition or deletion. The failure-effect and failure-configuration characteristics of ring networks are poor since a single failure in a path or a PE interface causes a break in the ring. In order to mask the fault, a fully-redundant ring path is required along with a bypass switching capability in the PE interfaces. A second failure can be catastrophic and cause isolation of certain nodes.

The logical complexity of communications in a ring network is low as a PE must only relay messages, originate messages and transmit them to a single or multiple destinations, recognize messages destined for itself, and "strip" off messages when required. The bandwidth of the single loop is a potential bottleneck as communication rates increase.

Most ring networks implemented have used the bit-serial data links as communication paths between PEs. This, along with delays associated in relaying messages, has resulted in significant increases in message transit times around the ring. This network is usually implemented where reliability and performance requirements are not stringent.

The Distributed Computer System (DCS), at the University of California, Irvine, is the best-known example of a ring network (Farber 1973). The DCS consists of five minicomputers and a number of peripheral devices located around the campus. The loop is bit-serial and operates at a data rate of 2.3 megabits/second. Variable-length messages can circulate simultaneously. Fault tolerance is provided by a redundant loop and bypass switches. Messages are sent to a logical process rather than to a physical processor. The ring interface recognizes the address and accepts the message, thus allowing communication to be independent of the number of processors and process/processor assignments.

2.2 INTERCONNECTION NETWORK

The complete interconnection network shown in Figure 2-2 is perhaps the simplest design type in the taxonomy. Each processor is connected to every other processor in the system by a dedicated path or link and messages between processors are transferred only on the path connecting them. The source processor must select the path to the destination processor from among the several paths available, and all processors must be capable of handling incoming messages from many paths.

The addition of the nth processor to a complete interconnection network requires the addition of n-1 paths between it and the other processors. Also, the processors must have facilities for accepting the new PE as a data source. Thus, the interfaces must have a minimum of M-1 parts, where M is the maximum size of the system. This all contributes to a poor cost-modularity for this network topology.

Failure of a path or processor is handled easily in an interconnection network as the failed components can be disconnected from the system. This architecture forces a location addressing policy to reduce the total network traffic low. Logical processor addressing would have the messages traveling on too many links.

The partial interconnection network topology differs from the complete interconnection network topology in that at least one processor is not connected to every other processor in the system. This one processor, however, must be connected to at least two other processors. This topology is shown in Figure 2-3.

Interconnection networks have the advantage that they may be geographically either localized or dispersed.

2.3 GLOBAL BUS NETWORK

The global bus architecture illustrated in Figure 2-4 consists of a number of processing elements interconnected by a common or global bus. Access to the bus is determined by an allocation scheme with messages sent from the source PE onto the bus. Messages are recognized and accepted by the appropriate PE interface as in logical processor addressing.

Additional PEs may be added to the system with little impact on the remainder of the system. In order to increase performance it is usually necessary to replicate the bus or to change the implementation of the entire bus, options which have a significant impact on the design of the bus interfaces of the system.

A failed processing element or processor interface requires no hardware reconfiguration to continue system operation. Failures of the bus, however, are catastrophic and replication is required for continued operation after a bus failure. The fixed bandwidth of the bus poses potential problems as the data rates are increased.

2.4 STAR NETWORK

The star network topology is comprised of a central switching element to which a number of processors are connected, each by a single bidirectional link. The central switch is the apparent

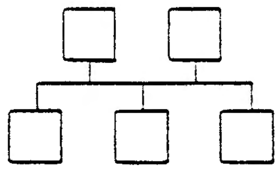


Figure 2-4. Global Bus Network Topology

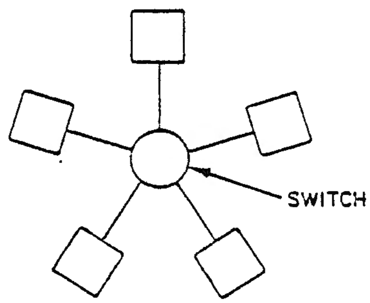


Figure 2-5. Star Network Topology

destination and source for all messages. This network topology is shown in Figure 2-5.

A failure of a processor element, processor interface, or path requires no hardware reconfiguration of the system. The failure of the switch is catastrophic, however. Message traffic at the switch can be a problem with this design. The switch must be able to accommodate additional PEs as each processor must have its own path to the central switch.

Adequate information in the form of routing tables must be provided within the switching resource to permit communications to occur.

3.0 FUNCTIONAL PARTITIONING

A real-time system was selected for evaluation of performance when operating under different network configurations. The objective was to compare the performance based on average message delay times associated with each network topology. The network topologies examined in this study are partial interconnection, ring and global bus and are shown in Figures 3.1 through 3.3. The complete interconnection network topology contained more links than necessary for this application and was not studied further. The star network topology was eliminated from the candidate set of architectures due to its central point of failure at the switch.

The computer software of the system chosen for the evaluation currently resides in a centralized computer system. The software program is comprised of an executive program, several functional modules and a global data base. The existing system was examined to determine if partitioning could be accomplished in a logical manner.

The fact that it was designed in a modular fashion enabled the system to be partitioned in a straight-forward manner. Experience has shown that a typical design for the system would include four (4) interactive display consoles, a large screen display, a horizontal plotter, a data base controller, an input data processor and a

Figure 3-1. Interconnection Network

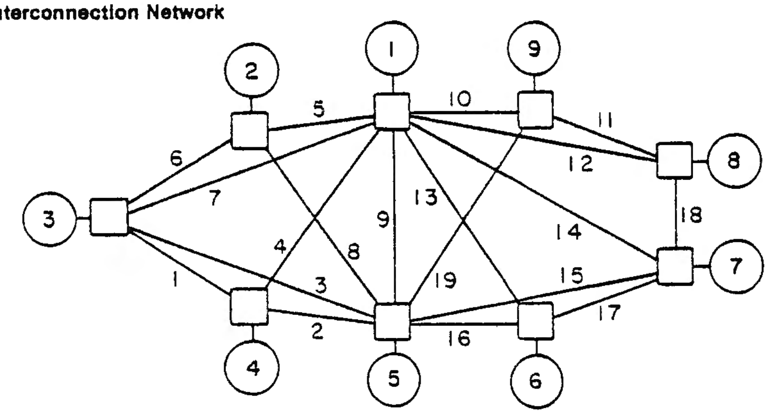


Figure 3-2. Ring Network

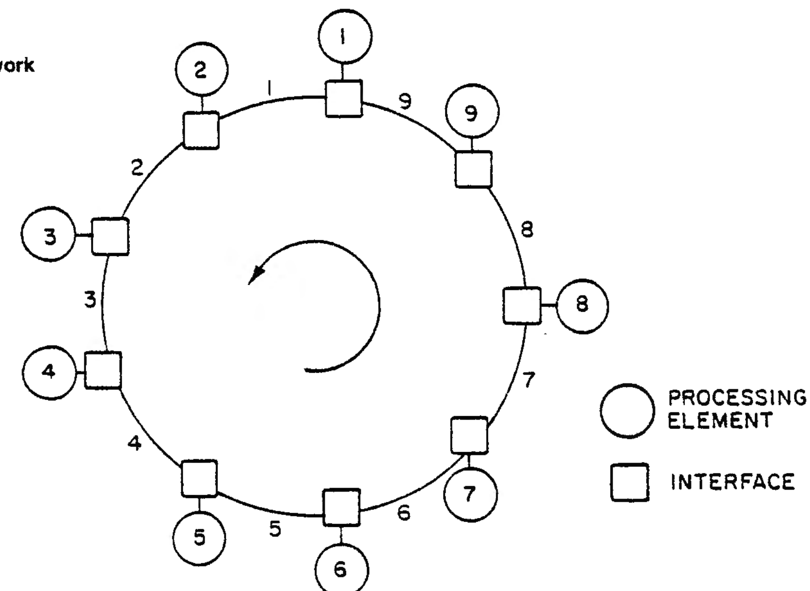
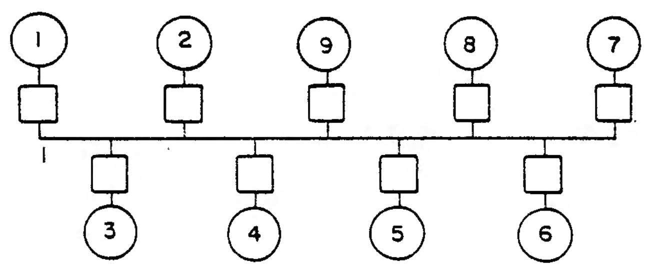


Figure 3-3. Global Bus Network



communications controller. Thus, a design was chosen with nine (9) nodes in the system. Including an embedded processor in each node was intended to minimize the response time and also keep the network message traffic as low as possible.

A system configuration was postulated to exercise the network in a realistic manner. Functions were allocated to the nodes as follows:

Node 1 - Input Data Processor

Node 2 - Object Motion Computations

Node 3 - Data Base Controller

Node 4 - Time Bearing Presentation

Node 5 - Communications Controller

Node 6 - Operations Summary

Node 7 - Vehicle Computations

Node 8 - Geographic Situation Presentation

Node 9 - Object Motion Computations

Nodes 1, 3, 5 and 7 are fixed-function nodes while the functions in the remaining nodes are operator selectable.

A determination was made regarding the accesses to the global data base by software modules resident in each node. Portions of the global data base at the Data Base Controller node were replicated at the other nodes. Next, each node was examined to determine the data field updates necessary for each data table resident at the node and a message traffic flow matrix developed as shown in Table A-1. The node data field traffic requirements are given in Table A-2.

A data table traffic matrix was constructed to illustrate the amount of 16- and 32-bit traffic in bits per second required from source to destination nodes as shown in Table A-3. Also determined was the data field traffic requirements in fields per second at each node as shown in Table A-4.

3.1 INTERCONNECTION NETWORK

The interconnection network design originated with a complete interconnection network. Links with low message traffic were removed from the network where traffic could be routed on other links without causing excessive loading. For study purposes, however, links 6 and 8 are relatively lightly loaded while link 7 is heavily loaded.

Message routing in the interconnection topology network, which was determined in the design process, is shown in Table A-8. Three message lengths are defined for purposes of this study in network performance evaluation and are as follows:

Short Message: 16 32-bit words = 512 bits

Medium Message: 32 32-bit words = 1024 bits

Long Message: 64 32-bit words = 2048 bits

The number of data bits per second is shown in Table A-3. From this, the number of short, medium and long messages/second from a source node to a destination node is computed as:

$$\text{Short: } \frac{34736 \text{ bits/second}}{512 \text{ bits/message}} = 67.84 \text{ short messages/second}$$

$$\text{Medium: } \frac{34736 \text{ bits/second}}{1024 \text{ bits/message}} = 33.92 \text{ medium messages/second}$$

$$\text{Long: } \frac{34736 \text{ bits/second}}{2048 \text{ bits/message}} = 16.96 \text{ long messages/second}$$

The complete presentation of short, medium and long messages per second from source to destination nodes and the associated link traffic is shown in Tables A-5 through A-7 and A-9 through A-11. This results in a value for link loading in messages per second, λ_i, where i identifies the particular link. Message arrivals are assumed to be Poisson in this study.

The total message traffic through each of the links is

$$\lambda = \sum_i \lambda_i$$

and the value for short messages is

$$\lambda = 1679 \text{ messages/second.}$$

Similarly, values for medium and long messages are found to be 871 and 464 messages/second respectively.

3.2 RING NETWORK

The ring network message routing is unidirectional and is shown in Table A-12. Message lengths are identical to the interconnected network messages.

Link traffic for the short, medium, and long messages is shown in Tables A-13, A-14 and A-15.

The total average message traffic through each of the links is

$$\lambda = \sum_i \lambda_i$$

and the value for short messages is

$$\lambda = 5630 \text{ messages/second.}$$

Also, the values for medium and long messages are 3903 messages/second and 1710 messages/second respectively.

In order to utilize more effectively the ring network features, a revised traffic matrix was developed under the premise that data would be sent to the most distant destination node only. Messages required by intermediate nodes also would be recognized by the processing element interface and a copy forwarded to the processing element. Thus, replicated messages would not be sent from a source node and network traffic could be reduced.

Traffic matrices for the revised loading scheme are shown in Tables A-16 through A-20. Link loading is given in Tables A-21, A-22 and A-23.

The total average message traffic through each of the links with the revised data for short messages is

$$\lambda = 2840 \text{ messages/second.}$$

Also, values of 1453 messages/second and 763 messages/second are obtained for the medium and long messages respectively.

3.3 GLOBAL BUS NETWORK

Message routing for the global bus network is shown in Table A-24. As there is only one link in this network, all message traffic is on link 1.

Link traffic in messages per second for the short, medium and long messages is shown in Table A-25.

Note that the total average message traffic through the link is identical to that for the ring network. Short messages have a value of 5630 messages/second; medium messages, 2903 messages/second; and long messages, 1710 messages/second.

A revised traffic matrix was also developed for the global bus network to utilize the features which could reduce traffic flow. The link traffic values in messages/second are again identical to the ring network and are 519, 265 and 141 in the short, medium and long messages respectively as shown in Table A-26.

4.0 NETWORK ANALYSIS

The three network topologies, which are interconnection, ring, and global bus, were analyzed while varying certain parameters in the system. These parameters are the network bandwidth, the message length and the network link capacity allocation strategy.

An objective of the analysis was to determine the average message delay for each combination of network variables.

4.1 NETWORK BANDWITH

Three network bandwidth values were defined for a gross examination of the system requirements. The bandwidths are 5 megabit, 10 megabit, and 20 megabit networks. These values are well within the state-of-the-art and are typical for real-time systems similar to the one being examined. In order to provide a further refinement of the requirements, bandwidths values of 1, 2, 3 and 4 megabits/second were studied.

4.2 MESSAGE LENGTH

In addition to message data, each message has appended to it 4 16-bit words of overhead to provide message length, source, destination and time information.

The average message length, $1/\mu_i$ in bits, is computed as:

Short Message: 512 bits/message + 64 bits overhead = 576 bits

Medium Message: 1024 bits/message + 64 bits overhead = 1088 bits

Long Message: 2048 bits/message + 64 bits overhead = 2112 bits.

The number of data bits/second on a link is determined as follows:

2171 data fields/second X 16 bits/data field = 34736 bits/second.

4.3 CAPACITY ALLOCATION STRATEGY

The equal assignment strategy, proportional assignment strategy, and optimum capacity assignment strategy were utilized in the network analysis (Schwartz 1977).

4.3.1 EQUAL CAPACITY ASSIGNMENT STRATEGY

An equal assignment strategy is one in which the total capacity C is simply divided equally among all the links, independent of the traffic on the link. In the case where the total capacity is 5 megabits/second and there are 9 links

$$C_i = 555{,}556 \text{ bits/second.}$$

4.3.2 PROPORTIONAL CAPACITY ASSIGNMENT STRATEGY

A proportional assignment strategy in which C is proportional to the traffic demand λ_i has

$$C_i \mid prop = \frac{C\lambda i}{\lambda}$$

Link 1 of the ring network had

$$C_i \mid prop = 929{,}840 \text{ bits/second.}$$

4.3.3 OPTIMUM CAPACITY ASSIGNMENT STRATEGY

The optimum capacity assignment is intended to minimize the average time delay throughout the network and is given as (Schwartz 1977)

$$C_i \mid opt = \frac{\lambda_i}{\mu_i} + \frac{C(1-\rho)\sqrt{\lambda_i/\mu_i}}{\sum_j \sqrt{\lambda_j/\mu_j}} .$$

Link traffic demand λ_i and the average message length $1/\mu_i$ are given for a typical case. C is the overall capacity of the network and is fixed. The network traffic intensity factor, ρ, is found by

$$\rho = \lambda/\mu C$$

Note that the form of the optimum capacity expression has two parts. The first, λ_i/μ_i, represents the absolute minimum capacity assignment that must be allocated to link i to enable the traffic over that link to be transmitted. The second part then allocates the remaining capacity to each link following a square-root assignment strategy. An example is given in Appendix B for the interconnection network using short messages.

The traffic intensity parameter for the interconnection networks is

$$\rho = \frac{\lambda}{\mu C} = 0.1934$$

4.4 DELAY ANALYSIS

The objective now is to solve for T, the average message delay in an M-channel, N-node model. It is assumed that there is a fixed routing procedure for the message traffic in each of the networks examined (Kleinrock 1976).

The path taken by messages that originate at node j and that are destinated for node k is denoted by π_{jk}. Also, the ith channel with capacity C_i is included in the path π_{jk} if that channel is traversed by messages using this path. Thus, it can be said that the average rate of message flow, λ_i, on the ith channel is equal to the sum of the average message flow rates of all paths that use this channel that is

$$\left(\lambda_i = \sum_j \sum_k \gamma_{jk} \atop j,k : C_i \in \pi_{jk} \right) \tag{4-1}$$

The total traffic within the network is given by

$$\lambda = \sum_{i=1}^{M} \lambda_i$$

The following quantitives are now defined as

Z_{jk} = E [message delay for a message whose origin is j and whose destination is k]

T_i = E [time spent waiting for and using the ith channel]

where Z_{jk} is the sum of the average delays encountered by a message in using the various channels along the path π_{jk}. T_i is the average time in a process where the process is defined as the ith channel (a server) plus a queue of messages in front of that channel. Z_{jk} is now written as

$$Z_{jk} = \sum_{i:C_i \in \pi_{jk}} T_i \tag{4-2}$$

The average message delay may be expressed in terms of its single channel components, where

$$T = \sum_{i=1}^{M} \frac{\lambda i}{\gamma} T_i \tag{4-3}$$

and M is the number communications channels.

Next a solution is found for a message's average system time in a single channel that is deeply embedded within a communications network. Jackson (1957), in studying network problems, established the result that this embedded channel offered a solution identical to that of the same channel acting independently from the network but with Poisson arrivals at a rate equal to that offered by the networks. However, in our model there is a dependence among the interarrival and service times. Kleinrock (1976) concludes that we want this dependence to disappear and in fact this dependence can be reduced to the point where we have approximate independence. This is based on the assumption that messages leaving the node on a given channel had entered the node from distinct channels or messages entering on the same channel depart on distinct channels. The independence assumption states that each time a message is received at a node within the network, a new message length is chosen from the exponential distribution. We know this is not true as a message maintains its length as it passes through the network, but the effect of the assumption on the performance measure T has been shown to be negligible in most networks.

Utilizing the isolated channel concept, the ith channel is represented as an M/M/1 system with Poisson arrivals at a rate λ_i and exponential service times of mean $1/\mu C_i$ seconds. The solution for T_i is given as

$$T_i = \frac{1}{\mu C_i - \lambda_i} \tag{4-4}$$

This assumes Poisson message arrivals, exponentially distributed message lengths, and an infinite buffer for the queue. It is assumed that all messages in the network have the same average length, $1/\mu$. This delay includes the time taken to transmit an average message plus the message buffering delay (Schwartz 1977).

From (4-3) and (4-4) the following is obtained

$$T = \sum_{i=1}^{M} \frac{\lambda i}{\gamma} \left[\frac{1}{\mu C_i - \lambda_i} \right] \tag{4-5}$$

An illustrative example which results in a solution for the average message delay is given in Appendix B.1.

4.4.1 PROGRAM NETWORK

A FORTRAN program was developed to aid in the analysis of network topologies. Program Network computes the average message delay for message traffic between nodes in a nine-node network. The network topologies examined in the program are ring, partial interconnection and global bus.

Capacity allocation strategies included in the program are equal assignment, proportional assignment and optimum assignment.

The program provides for the insertion of three network bandwidth capacities and three message average lengths for evaluation purposes.

In addition to providing the average message delay time for each combination of parameter values, the bandwidth capacity and average delay time which messages encounter on each link of the network are given.

4.4.2 ANALYSIS RESULTS

Equations for analysis of the three network configurations are included in Program Network and runs were conducted varying each of the parameters. Short, medium and long message lengths were used as were 1-, 2-, 3-, 4-, 5-, 10-, and 20- megabit bandwidths for the network. Another variable in the parametric study is the capacity assignment strategy where the equal, proportional and optimum capacity assignment strategies were utilized.

Average message delay data are shown in tables C-1 through C-9. Data are presented for five network cases - interconnection, ring, global bus, ring (with revised message traffic) and global bus (with revised message traffic). Average message delay time vs. message size and assignment strategy is shown for each network bandwidth.

The global bus network provides the lowest average message delay for all cases as shown in Tables C-1 through C-3 and is the only topology satisfactory at the 1-megabit bandwidth capacity level for the equal capacity assignment strategy. As can be seen in these figures, the 4-megabit network provides a sufficiently high traffic capacity for the application so that all network topologies perform satisfactorily for short and medium messages, i.e. less than 25 milli-seconds delay.

The average message delays for the proportional capacity assignment strategy with short, medium and long messages are given in Figures C-4 through C-6. While not performing as well as the global bus discussed earlier, the ring (with modified data) and the interconnection topologies perform well at the 4 megabit capacity for all message lengths.

An optimum capacity assignment strategy improved the ring (modified data) and interconnection network topologies with both performing well at the 2-megabit capacity for short messages. This is illustrated in Table C-7.

An examination of the data reveals that the lightly loaded traffic links receive less capacity than do the heavily loaded traffic links in the proportional and optimum capacity assignment strategies. Links 6 and 7 illustrate this situation.

The proportional capacity allocation strategy provides a capacity of 23823.70 bits/second for link 6 with an 8 messages/second loading. This results in an average delay over the link of 30 milliseconds. Link 7 is given a capacity of 1060154 bits/second for a loading of 356 messages/second resulting in an average message delay of 0.67 milliseconds. These data are for short message lengths.

The optimum capacity allocation strategy reduces the spread in message delay times between the lightly and heavily loaded links. Link 6 has a capacity of 72373 bits/second and an average message delay of 8.5 milliseconds. Link 7 is allocated a capacity of 657109 bits/second and results in an average message delay of 1.3 milliseconds.

Thus, the light user is penalized in favor of the heavy user in order to minimize the average time delay.

5.0 NETWORK SIMULATION

A GPSS simulation was developed for the nine-node distributed computing system with the global bus network topology. Each node (or processing element) operates in a round-robin fashion. Node processing times are input as initial values and the channel delay time is based on the particular bandwidth being considered.

The simulation, which runs under General Purpose Simulation System/360, is utilized in a parametric study of the network message delay times including the processor and channel components.

5.1 SIMULATION RUNS

Several simulation experiments were conducted to examine the total message delay (or transit) time in the network. The parameters in the program are (1) processing times for each of the nine nodes, (2) the message arrival rates and (3) the channel delay times.

The processing time parameter is determined by dividing the number of instructions executed per cycle as shown in Table D-1 by the processing capability. Values of 0.2, 0.4 and 0.6 million instructions per second (MIPS) are utilized for the study. The node processing times are given in Table D-2.

The message arrival rate is varied to provide times of 50, 100 and 200 milliseconds to determine the effect of this parameter on message delay times.

Channel delay times for the global bus topology with network bandwidths of 1, 2, 3 and 4 megabits per second are utilized in the experiment.

The simulation model provides for two-node, three-node and four-node serial communication paths with the global bus handling the node-to-node message traffic. The two-node communication paths can have any node transmitting to another node. The three-node communication path includes nodes 1, 9 and 6 in that order, while the four-node path includes nodes 1, 2, 7 and 5. Data are tabulated during each transmission and an overall message delay is computed for all transactions in the model.

5.2 TEST OBJECTIVE

Experimental runs were conducted to determine a combination of global bus bandwidth, message arrival rate and node processing capability which would meet the overall message delay time objective of 200 milliseconds and four-node processing time of 300 milliseconds.

5.3 SIMULATION RESULTS

Several runs were conducted for the combination of parameters mentioned earlier. An examination of the tabulated message delay data provided a relative performance standing for each test case as shown in Table 5-1. The relative performance was based on the threshold message delays of 250 milliseconds for the overall average delay and 350 milliseconds for the four-node message delay. Data for the two- and three-node cases were expected to fall between these two values. Detailed results are presented in Table D-3 and in Figures D-1 through D-3.

It is interesting that with a 50-millisecond message arrival rate, the message delay is unaffected by network bandwidths. The 100-millisecond message arrival rate indicates a slight decrease in overall message delay as the bandwidth increases; whereas at the 200-millisecond rate, there is a pronounced decrease in overall message delay as bandwidth increases.

The five parametric combinations indicating acceptable performance were selected for further examination. Four additional test runs were made for each case with random number seeds as shown in Table D-4 selected from a random number table (Lapin 1975). The runs were repeated with different random numbers for the same sample size to give a set of independent determinations of the sample mean

Table 5.1. Global Bus Network Performance

RUN	PROCESSOR, MIPS	MESSAGE ARRIVAL RATE, MSEC	BAND WIDTH, MEGABITS	PERFORMANCE
0512	0.2	50	1	NOT ACCEPTABLE
0514	0.4	50	1	NOT ACCEPTABLE
0516	0.6	50	1	ACCEPTABLE
0522	0.2	50	2	NOT ACCEPTABLE
0524	0.4	50	2	NOT ACCEPTABLE
0526	0.6	50	2	MARGINALLY ACCEPTABLE
0532	0.2	50	3	NOT ACCEPTABLE
0534	0.4	50	3	NOT ACCEPTABLE
0536	0.6	50	3	ACCEPTABLE
0542	0.2	50	4	NOT ACCEPTABLE
0544	0.4	50	4	NOT ACCEPTABLE
0546	0.6	50	4	ACCEPTABLE
1012	0.2	100	1	NOT ACCEPTABLE
1014	0.4	100	1	NOT ACCEPTABLE
1016	0.6	100	1	NOT ACCEPTABLE
1022	0.2	100	2	NOT ACCEPTABLE
1024	0.4	100	2	NOT ACCEPTABLE
1026	0.6	100	2	MARGINALLY ACCEPTABLE
1032	0.2	100	3	NOT ACCEPTABLE
1034	0.4	100	3	NOT ACCEPTABLE
1036	0.6	100	3	ACCEPTABLE
1042	0.2	100	4	NOT ACCEPTABLE
1044	0.4	100	4	NOT ACCEPTABLE
1046	0.6	100	4	ACCEPTABLE

Table 5-1. Global Bus Network Performance (Cont.)

RUN	PROCESSOR MIPS	MESSAGE ARRIVAL RATE, MSEC	BAND-WIDTH, MEGABITS	PERFORMANCE
2012	0.2	200	1	NOT ACCEPTABLE
2014	0.4	200	1	NOT ACCEPTABLE
2016	0.6	200	1	NOT ACCEPTABLE
2022	0.2	200	2	NOT ACCEPTABLE
2024	0.4	200	2	NOT ACCEPTABLE
2026	0.6	200	2	NOT ACCEPTABLE
2032	0.2	200	3	NOT ACCEPTABLE
2034	0.4	200	3	NOT ACCEPTABLE
2036	0.6	200	3	NOT ACCEPTABLE
2042	0.2	200	4	NOT ACCEPTABLE
2044	0.4	200	4	NOT ACCEPTABLE
2046	0.6	200	4	MARGINALLY ACCEPTABLE

Table 5-2. Global Bus Network Simulation Message Delay Data, μ Seconds Repeated Runs

RUN NUMBER	MESSAGE DELAY STATISTICS	MESSAGE PATH, NODES			
		OVERALL	TWO	THREE	FOUR
0516	MEAN	1610	1447	2800	3327
	VARIANCE	255	18	8543	1509
	90% CONFIDENCE INTERVAL	± 15	± 4	± 89	± 37
0536	MEAN	1529	1385	2534	3034
	VARIANCE	47	72	19	183
	90% CONFIDENCE INTERVAL	± 7	± 8	± 4	± 13
0546	MEAN	1521	1383	2508	2994
	VARIANCE	44	76	3	196
	90% CONFIDENCE INTERVAL	± 6	± 8	± 2	± 13
1036	MEAN	1669	1482	2929	3591
	VARIANCE	319	11	3769	3985
	90% CONFIDENCE INTERVAL	± 17	± 3	± 59	± 60
1046	MEAN	1635	1460	2837	3439
	VARIANCE	416	49	1212	1595
	90% CONFIDENCE INTERVAL	± 20	± 7	± 33	± 38

Figure 5-1. Global Bus Network Simulation
Message Delay, μ Seconds With 90%
Confidence Interval – Run Number 0516

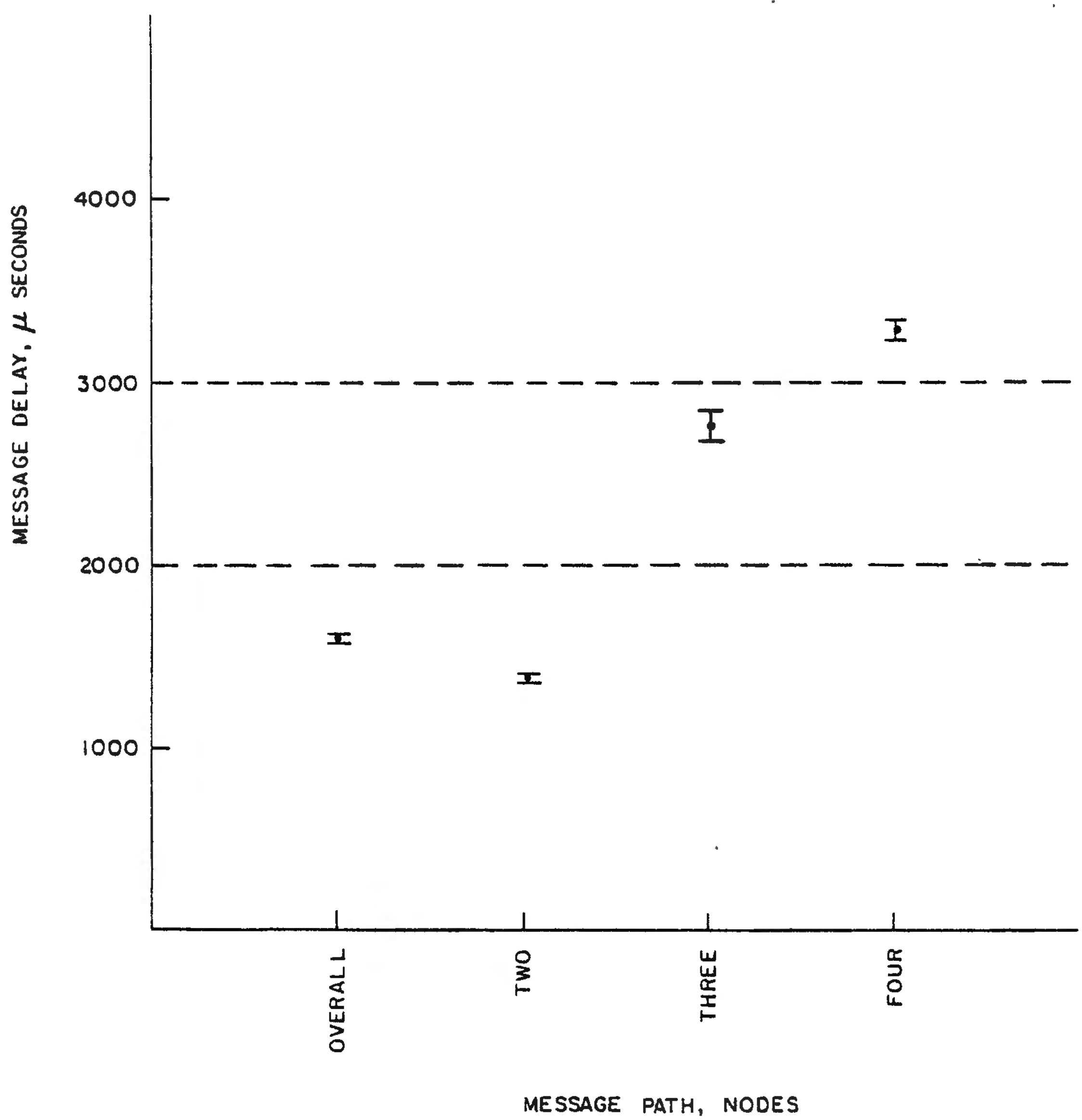


Figure 5-2. Global Bus Network Simulation
Message Delay, μ Seconds With 90%
Confidence Interval - Run Number 0536

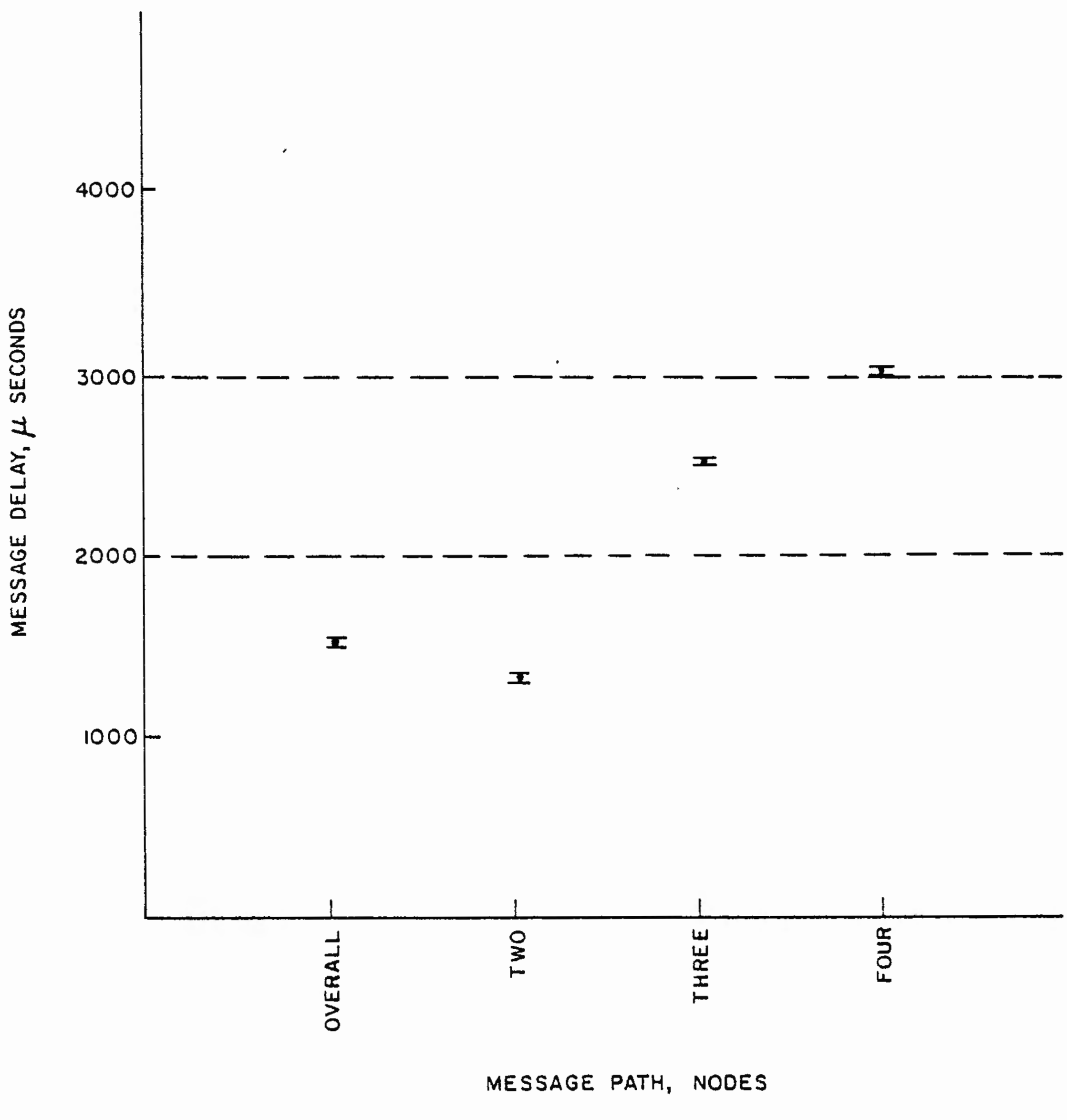


Figure 5-3. Global Bus Network Simulation
Message Delay, μ Seconds With 90%
Confidence Interval - Run Number 0546

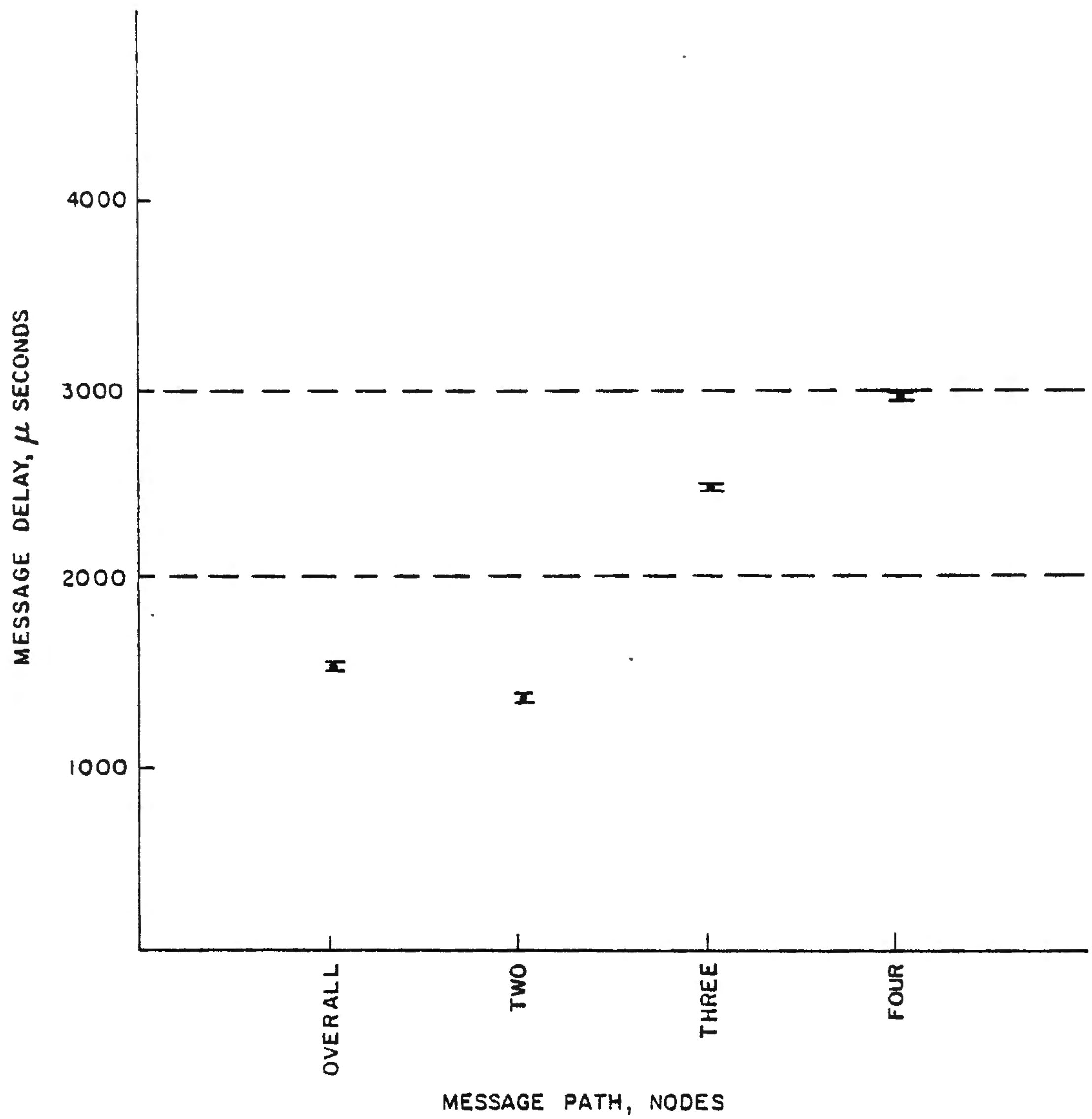


Figure 5-4. Global Bus Network Simulation Message Delay, μ Seconds With 90% Confidence Interval - Run Number 1036

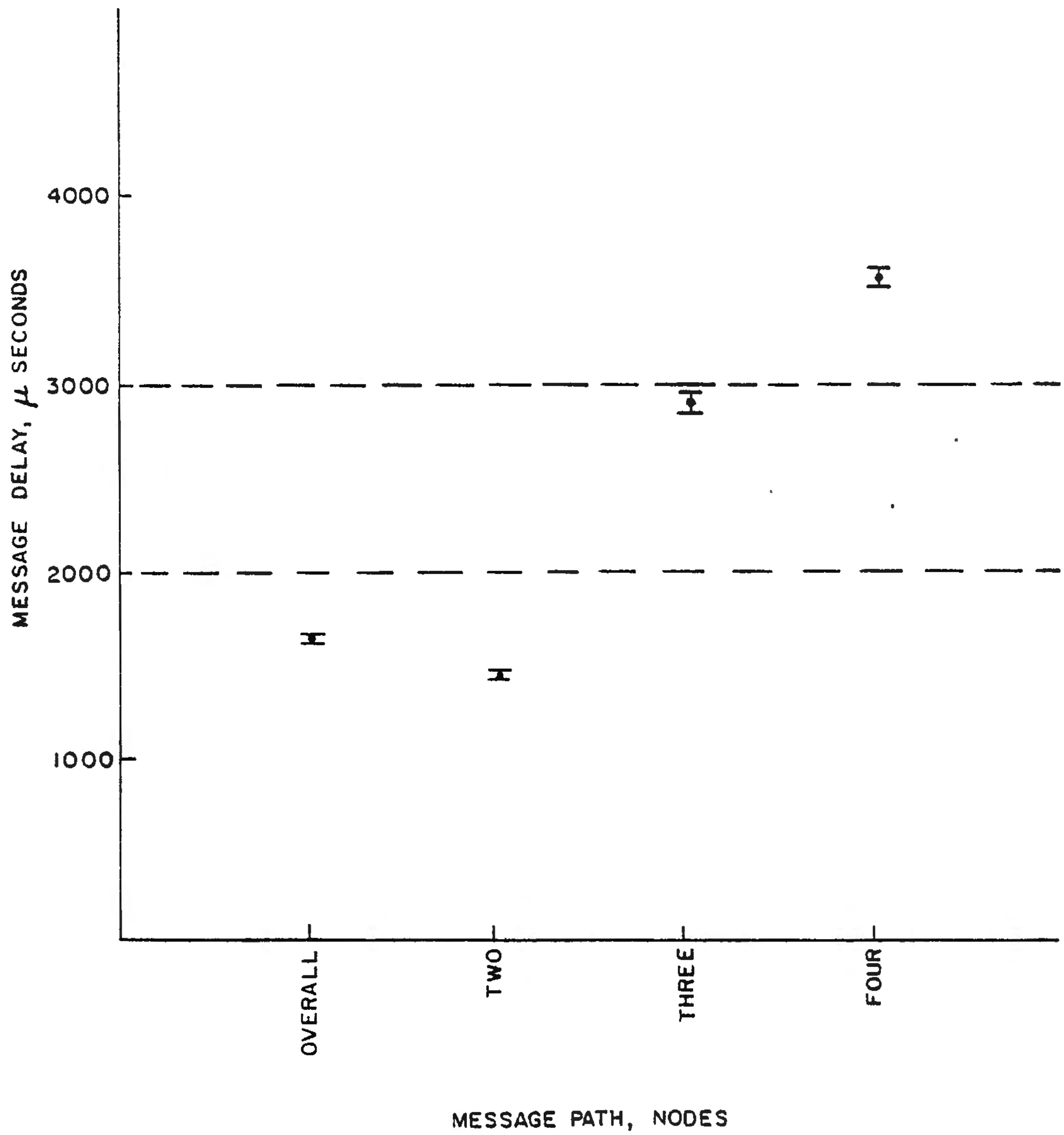
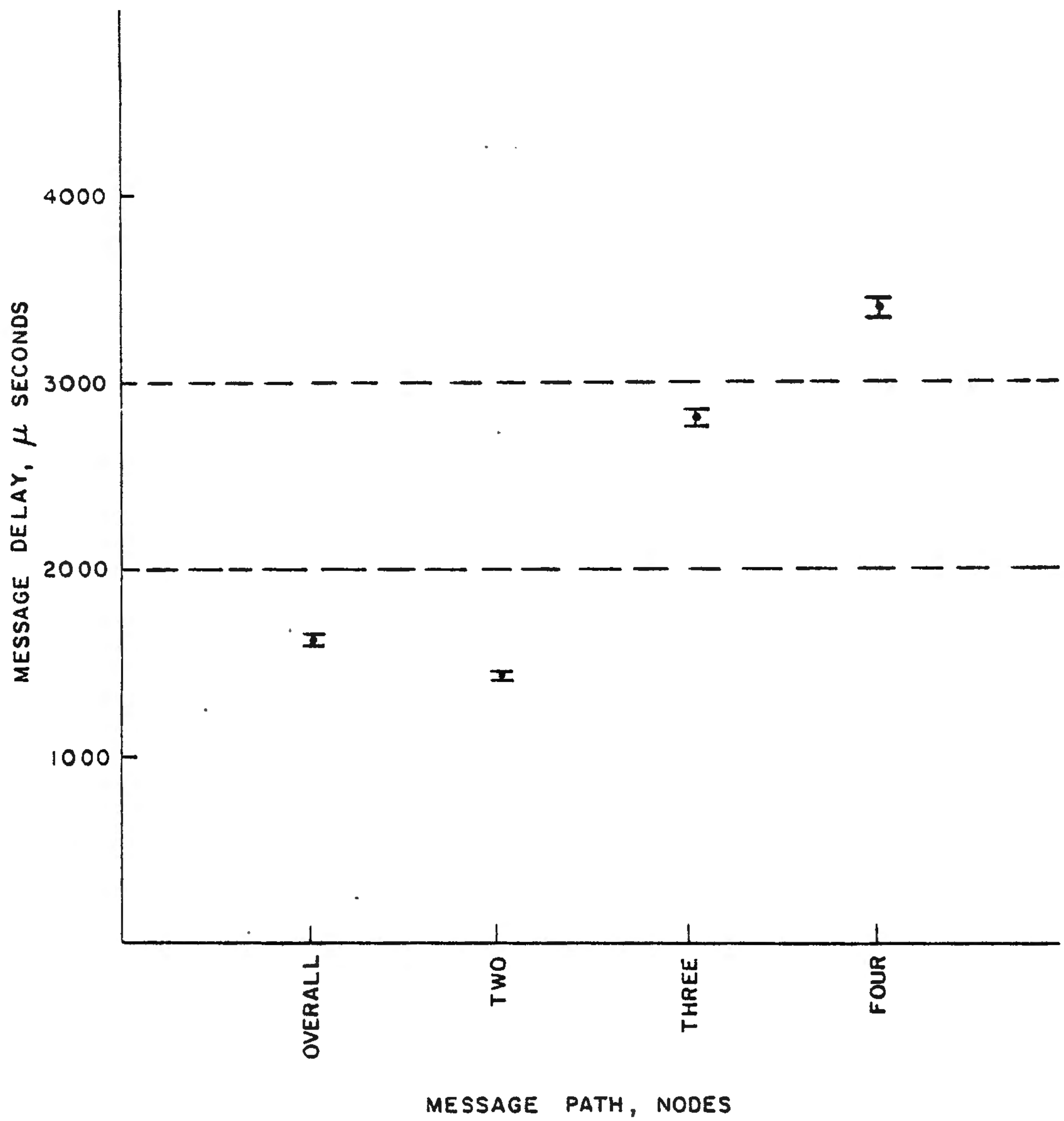


Figure 5-5. Global Bus Network Simulation
Message Delay, μ Seconds With 90%
Confidence Interval - Run Number 1046



(Gordon 1969). The results of these runs are presented in Table D-5. The data for each set of runs were then used to determine a mean, variance and 90% confidence interval as shown in Table 5-2. A sample calculation is provided in Appendix D. These results also appear in Figures 5-1 through 5-5.

While all five cases had an overall message delay well below the 200 millisecond time objective, only one case met the 300 millisecond delay for the four-node communications path. This run, number 0546, had a 50 millisecond message arrival rate, a 4 megabit bandwidth and a 0.6, MIPS processor capability. Here, the increase in bandwidth from 3 to 4 megabits affected a decrease in message delay time. The 3 megabit case, run number 0536, had a four-node communication delay slightly above 300 milliseconds.

The large difference in variances in cases such as run number 0516 (three-node) and run number 0546 (three-node) caused some interest. This situation was thought to be due to the variable number of transactions occurring in the simulation of the two-, three-, and four-node message paths, which are 90.2%, 3.9% and 5.9% of the transactions respectively.

Additional sets of runs were made for these two run numbers with the two-, three-, and four-node message path transactions being 33%, 33% and 33% respectively. The differences in variance were reduced significantly, i.e. the run number 0516 (three-node) variance decreased from 8543 to 125 while run 0546 (three-node) variance increased from 3 to 35. Thus, the theory that the difference in numbers of transactions contributed greatly to the variance results was substantiated. Interestingly, the mean message delay for each of the reruns varied only slightly from the original run data.

6.0 CONCLUSIONS

The analysis conducted in this investigation of a local network topology showed that the global bus network provides superior performance over the interconnection and ring networks where performance is based on average message delay time. Also, short messages performed better than medium and long messages.

A simulation model introduced processor delays in addition to channel delays in the determination of average message delay time. The experiment showed that the fast processor (0.6 MIPS) with a 50-millisecond message arrival rate and a 4-megabit bandwidth global bus network topology is satisfactory for the application under study. The overall message delay time is less than 200 milliseconds and the four-node serial communication message delay time is less than 300 milliseconds.

The methodology developed in this paper is viewed as a useful tool in the system design process. Software requirements are first determined based on the functional system requirements. After the desired system response time is determined, the software and hardware specifications may then be defined.

As computer systems change rather frequently due to improvements and modifications, the techniques developed in this analysis and simulation have further application in that they provide for an assessment regarding network performance due to proposed changes. Another variation of the network performance analysis problem would be to fix one of the parameters such as processor capacity, assuming only one processor is available for an application, and vary the bandwidth and message arrival rate parameters until a satisfactory message delay time is found.

A logical extension of this effort would be to merge the analysis and simulation programs into a single program capable of handling n nodes and i links or channels. Added to this would be an interactive capability with a display console for input/ouput resulting in an improved software tool for utilization in the design of advanced computer systems.

An expansion of the global bus simulation could include a replication of the global bus and a traffic controller to regulate the flow of messages over each bus.

7.0 LITERATURE CITED

George A. Anderson and E. Douglas Jensen, "Computer Interconnection Structures: Taxonomy, Characteristics, and Examples," ACM Computing Surveys, Vol. 7, No. 4, December 1975, pp. 197-213.

David J. Farber et al., "The Distributed Computing System," IEEE Compcon 73 Proceedings, March 1973.

Geoffrey Gordon, System Simulation, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1969, pp. 277-290.

J. R. Jackson, "Networks of Waiting Lines," Operations Research, 5, 1957, pp. 518-521.

Leonard Kleinrock, Queuing Systems, John Wiley and Sons, Inc., New York, New York, 1976, pp. 292-304, 314-340.

Lawrence L. Lapin, Statistics: Meaning and Method, Harcourt Brace Jovanovich, New York, 1975, pp. 265-267, 552.

Mischa Schwartz, Computer-Communication Network Design and Analysis, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, pp. 58-68, 71-82.

APPENDIX A

DATA TABLES

A.0 General Tables

Table A-1. Message Traffic Flow Matrix. This table illustrates the node-to-node traffic requirements. For example, and "x" in location (1,2) indicates data must flow from source node 1 to destination node 2.

Table A-2. Node Data Field Traffic Requirements. The Node Data Field Traffic Requirements Table shows the actual data field requirements. The data tables in each node which have data fields set and used by modules resident in the node are identified. Thus, the traffic requirements can be determined. For example, node 1 uses 791 data fields/second and sets 400 data fields/second in table FTDDSVT. Nodes 2, 4, 5, 6, 8, and 9 use data from FTDDSVT. Thus, 400 data fields/second are transmitted to these nodes from node 1. Node 4 sets 20 fields/second in this table and so 20 fields/second are transmitted to nodes 1, 2, 5, 6, 8, and 9. As a copy of all tables is maintained in the data base controller (node 3) the 400 and 20 data fields/second are sent to node 3 also (Bryden 1979).

Table A-3. Network Traffic Matrix. This table provides three entries for each source-destination combination. These are all given in data bits/second without overhead for: 16-bit data fields

32-bit data fields

32-bit control messages

The entries in location (1,3) are obtained as follows:

5232 data fields/second X 16 bits/field = 83712 bits/second

1480 data fields/second X 32 bits/field = 47360 bits/second

10 messages/second X 8 fields/message X 32 bits/field = 2560 bits/second.

Table A-4. Data Fields Traffic Matrix. This table is merely a summation of the data fields presented in Table A-2. Example: A summation of the data fields transmitted from node 1 to node 2 in Table A-2 is

Σ = 400 +1130 + 12 + 6 + 420 + 8 + 195

= 2171 data fields/second and this value appears in location (1,2) of Table A-4. Also appearing is the value of 10 system control messages/second.

Tables A-5, A-6 and A-7. Network Traffic Matrix. These tables give the number of short, medium and long messages/second, respectively, for the data in Table A-3. Calculations to obtain the data for location (1,3) are given for each table:

Table A-5. (83712 bits/second) (16 words X 32 bits/word)

= 163.5 messages/second

(47360 bits/second) (16 words X 32 bits/word)
= 92.5 messages/second

(2560 bits/second) $\div$ (16 words X 32 bits/word)

= 5 messages/second

Table A-6. (83712 bits/second) $\div$ (32 words X 32 bits/word)

= 81.75 messages/second

(47360 bits/second) $\div$ (32 words X 32 bits/word)

= 46.25 messages/second

(2560 bits/second) $\div$ (32 words X 32 bits/word)

= 2.5 messages/second

Table A-7. (83712 bits/second) $\div$ (64 words X 32 bits/word)

= 40.88 messages/second

(47360 bits/second) $\div$ (64 words X 32 bits/word)

= 23.13 messages/second

(2560 bits/second) $\div$ (64 words X 32 bits/word)

= 1.25 messages/second

A.1 Interconnection Network Tables

Table A-8. Interconnection Network Node-Node Message Routing. This table illustrates the route each message takes as it goes from a source node to a destination node. For example, location (2,7) contain the entry 2-5-6-7. In this case, messages going from source node 2 to destination node 7 pass through the node interfaces at nodes 5 and 6 prior to arriving at node 7.

Table A-1. Message Traffic Flow Matrix

SOURCE NODE	DESTINATION NODE								
	1	2	3	4	5	6	7	8	9
1	—	X	X	X	X	X	X	X	X
2	X	—	X	X	X	X	X	X	
3	X	X	—	X		X		X	X
4	X	X	X	—	X	X	X	X	X
5	X		X		—	X	X		
6						—			
7	X		X		X		—		
8		X	X	X	X	X	X	—	X
9	X	X	X	X	X	X	X	X	—

Table A-2. Node Data Field Traffic Requirements, Fields / Second
16-Bit Data Fields Used / Sec by Node

TABLE NAME	NODE								
	1	2	3	4	5	6	7	8	9
FTDDSVT	791/400	28/0		18/20	37/0	31/0		12/0	28/0
FTDIBA	0/700				4/0				
FTDILA	0/380								
FTODI	0/440				58/330	20/0			
FTOLHT	0/6	4/0				6/0		6/0	4/0
FTOSDHT	0/8	5/0			10/0	12/0		6/0	5/0
FTTAS	0/220			1/20					
FTTCLAS	0/50				1/0		1/0		
FTTLIST	0/1130	10/10		7/10	8/0	120/0	3/0	320/600	10/10
FTWEAPON					51/130		8/20		
FTCFIDU	0/220					180/0		100/0	
FTFIDU	0/420	14/0		14/20	2/0				14/0
FTMRHT	0/195	10/9		1/0		140/0		200/0	10/9
FTDRHT	0/7								
FTSENST	0/30			1/20				6/0	
FTSPTRHT	2/30								
FTTHK	3/3								
FTDDSVT	13/110						1/0		
FTCTMLTS	76/240								
FTSST	35/150								
FTPL48	30/80				41/370		4/60		
FTCSSHT	420/12	3/5		1/2					3/5
FTKPMTRX	0/21								

Table A-2. Node Data Field Traffic Requirements, Fields / Second (Cont.)

TABLE NAME	NODE 1	2	3	4	5	6	7	8	9
FTPSHT	300/380								
FTM82OUT	0/30				60/600		9/430		
FTCSTATS		7/1		2/10		3/0	5/0	1/0	7/1
FTSSHT	0/220[a]	0/22				0/4[a]		0/112[a]	0/22
FTMSHT		0/22				0/2[a]			0/22
FTMK48RES					37/350		31/450		
FTMK48APT					22/10		37/50		
FTREVERB					0/144				
FTDIHT	0/260[b]			0/8[a]					
FTKSHT	0/140[b]	0/7[a]				0/8[a]		0/212[a]	0/7[a]
FTKSORU	0/40[b]								
FTKSST	0/820[b]								
FTDIHTL	112/12[b]			112/4[a]					
FTTLINK	10/1[b]			10/1[a]					
FTSSHT		112/4[a]							112/4[a]
FTMTR		0/4[a]							0/4[a]
FTMSHT		112/4[a]				0/2[a]		0/112[a]	112/4[a]
FTDBSL		0/1[a]							0/1[a]
FTCSTATM				0/1[a]		0/1[a]		0/1[a]	
FTDBTA				0/3[a]		0/10[a]			
FTDBTB				0/6[a]					
FTDBTAC				0/6[a]					
FTGEREM								0/1[a]	
FTOVER						0/1[a]			

Table A-2. Node Data Field Traffic Requirements, Fields / Second (Cont.)

TABLE NAME	NODE 1	2	3	4	5	6	7	8	9
FTOPTPDT						0/1[a]			
FTOPLIST						0/7[a]			
FTDBTA						0/9[a]			
FTACTIVE						0/6[a]			
FTACTIVA						0/6[a]			
FTACTIVB						0/6[a]			
FTOPOVLY						0/1[a]			

NOTES. 1. AN "a" DENOTES DISK 32-BIT READ AND WRITE OPERATION.

2. A "b" DENOTES DISK 32-BIT WRITE OPERATION.

3. A "ϕ" IN USED COLUMN INDICATES NODE DOES NOT REQUIRE DATA FROM ANOTHER NODE FOR THE TABLE.

Table A-3. Network Traffic Matrix, Bits / Second
A. 16-Bit Data Field
B. 32-Bit Data Field
C. 32- Bit Control Message

SOURCE NODE		DESTINATION NODE 1	2	3	4	5	6	7	8	9
1	A	—	34736	83712	38512	51648	37904	21920	31824	34736
	B	—	—	47360	—	—	—	—	—	—
	C	—	2560	2560	2560	2560	2560	2560	2560	2560
2	A	80	—	1104	400	160	320	176	320	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
3	A	—	—	—	—	—	—	—	—	—
	B	47776	640	—	928	—	2048	—	14016	640
	C	—	—	—	—	—	—	—	—	—
4	A	320	992	1632	—	800	640	320	960	992
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
5	A	5920	—	30944	—	—	5280	23360	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
6	A	—	—	—	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
7	A	960	—	16160	—	16160	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
8	A	—	9600	9600	9600	9600	9600	9600	—	9600
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
9	A	80	384	1104	400	160	320	176	320	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—

Table A-4. Data Field Traffic Matrix, Fields / Second
A. 16-Bit Data Field
B. 32-Bit Data Field
C. 32-Bit Control Message

SOURCE NODE		DESTINATION NODE								
		1	2	3	4	5	6	7	8	9
1	A	—	2171	5232	2407	3228	2369	1370	1989	2171
	B	—	—	1480	—	—	—	—	—	—
	C	—	10	10	10	10	10	10	10	10
2	A	5	—	69	25	10	20	11	20	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
3	A	—	—	—	—	—	—	—	—	—
	B	1493	20	—	29	—	64	—	438	20
	C	—	—	—	—	—	—	—	—	—
4	A	20	62	102	—	50	40	20	60	62
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
5	A	370	—	1934	—	—	330	1460	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
6	A	—	—	—	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
7	A	60	—	1010	—	1010	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
8	A	—	600	600	600	600	600	600	—	600
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
9	A	5	24	69	25	10	20	11	20	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—

Table A-5. Short Message Traffic, Messages / Second
A. 16-Bit Data Field
B. 32-Bit Data Field
C. 32-Bit Control Message

SOURCE NODE		DESTINATION NODE								
		1	2	3	4	5	6	7	8	9
1	A	—	67.84	163.50	75.22	100.88	74.03	42.81	62.16	67.84
	B	—	—	92.50	—	—	—	—	—	—
	C	—	5	5	5	5	5	5	5	5
2	A	0.16	—	2.16	0.78	0.31	0.63	0.34	0.63	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
3	A	—	—	—	—	—	—	—	—	—
	B	93.31	1.25	—	1.81	—	4.00	—	27.38	1.25
	C	—	—	—	—	—	—	—	—	—
4	A	0.63	1.94	3.19	—	1.56	1.25	0.63	1.88	1.94
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
5	A	11.56	—	60.44	—	—	10.31	45.63	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
6	A	—	—	—	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
7	A	1.88	—	31.56	—	31.56	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
8	A	—	18.75	18.75	18.75	18.75	18.75	18.75	—	18.75
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
9	A	0.16	0.75	2.16	0.78	0.31	0.63	0.34	0.63	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—

Table A-6. Medium Message Traffic, Messages / Second
A. 16-Bit Data Field
B. 32-Bit Data Field
C. 32-Bit Control Message

SOURCE NODE		DESTINATION NODE								
		1	2	3	4	5	6	7	8	9
1	A	—	33.92	81.75	37.61	50.44	37.02	21.41	31.08	33.92
	B	—	—	46.25	—	—	—	—	—	—
	C	—	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
2	A	0.08	—	1.08	0.39	0.16	0.31	0.17	0.31	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
3	A	—	—	—	—	—	—	—	—	—
	B	46.66	0.63	—	0.91	—	2.00	—	13.69	0.63
	C	—	—	—	—	—	—	—	—	—
4	A	0.31	0.97	1.59	—	0.78	0.63	0.31	0.94	0.97
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
5	A	5.78	—	30.22	—	—	5.16	22.81	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
6	A	—	—	—	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
7	A	0.94	—	15.78	—	15.78	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
8	A	—	9.38	9.38	9.38	9.38	9.38	9.38	—	9.38
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
9	A	0.08	0.38	1.08	0.39	0.16	0.31	0.17	0.31	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—

Table A-7. Long Message Traffic, Messages / Second
A. 16-Bit Data Field
B. 32-Bit Data Field
C. 32-Bit Control Message

SOURCE NODE		DESTINATION NODE								
		1	2	3	4	5	6	7	8	9
1	A	—	16.96	40.88	18.80	25.22	18.51	10.70	15.54	16.96
	B	—	—	21.13	—	—	—	—	—	—
	C	—	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
2	A	0.04	—	0.54	0.20	0.08	0.16	0.09	0.16	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
3	A	—	—	—	—	—	—	—	—	—
	B	23.33	0.31	—	0.45	—	1.00	—	6.84	0.31
	C	—	—	—	—	—	—	—	—	—
4	A	0.16	0.48	0.80	—	0.39	0.31	0.16	0.47	0.48
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
5	A	2.89	—	15.11	—	—	2.58	11.41	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
6	A	—	—	—	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
7	A	0.47	—	7.89	—	7.89	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
8	A	—	4.69	4.69	4.69	4.69	4.69	4.69	—	4.69
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
9	A	0.04	0.19	0.54	0.20	0.08	0.16	0.09	0.16	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—

Table A-9, A-10, and A-11. Interconnection Network Link Traffic. These tables contain the link traffic in messages/second (λ_i) for short, medium and long message lengths. The message traffic from Tables A-5, A-6, and A-7 are used in conjunction with the interconnection network message routing given in Table A-8 to arrive at a tabulation of λ_i for each network link.

A.2 Ring Network Tables

Table A-12. Ring Network Node-Node Message Routing. This table illustrates the route each message takes as it goes from a source node to a destination node. For example, location (3,5) contains the entry (3-4-5). In this case, messages going from source node 3 to destination node 5 pass through the node interface at node 4 prior to arriving at node 5.

Tables A-13, A-14, and A-15. Ring Network Link Traffic. These tables contain the link traffic in messages/second (λ_i) for short, medium and long message lengths. The message traffic data from Tables A-5, A-6, and A-7 are used in conjunction with the ring network message routing given in Tables A-12 to arrive at a tabulation of λ_i for each network link.

Note: The data traffic flow in these tables is designed such that if the same message packet is required at both nodes 5 and 6 and

Table A-8. Interconnection Network Node-Node Message Routing

SOURCE NODE	DESTINATION NODE								
	1	2	3	4	5	6	7	8	9
1	—	1-2	1-3	1-4	1-5	1-6	1-7	1-8	1-9
2	2-1	—	2-3	2-3-4	2-5	2-5-6	2-5-6-7	2-5-9-8	2-5-9
3	3-1	3-2	—	3-4	3-5	3-4-5-6	3-4-5-6-7	3-4-5-9-8	3-4-5-9
4	4-1	4-3-2	4-3	—	4-5	4-5-6	4-5-6-7	4-5-9-8	4-5-9
5	5-1	5-2	5-3	5-4	—	5-6	5-7	5-9-8	5-9
6	6-1	6-5-2	6-5-4-3	6-5-4	6-5	—	6-7	6-7-8	6-5-9
7	7-1	7-6-5-2	7-6-5-4-3	7-6-5-4	7-5	7-6	—	7-8	7-6-5-9
8	8-1	8-9-5-2	8-9-5-4-3	8-9-5-4	8-9-5	8-7-6	8-7	—	8-9
9	9-1	9-5-2	9-5-4-3	9-5-4	9-5	9-5-6	9-5-6-7	9-8	—

Table A-9. Interconnection Network, Messages / Second
Short Messages

SOURCE NODE	NETWORK LINK																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1				81	73		262		106	73		68	80	48					
2	1				1	4		4			1					2	1		1
3	36	34				2	94				28					4			30
4	6	9		1		2					2					3	1		4
5			61						12						46	11			
6																			
7	32	32												2	32	32	32		
8	19	38						19			95						19	38	76
9	3	4						1		1						2	1		8
TOTAL, λ_i	97	117	61	82	74	8	356	24	118	74	127	68	80	50	78	54	54	38	119

Table A-10. Interconnection Network, Messages / Second
Medium Messages

SOURCE NODE	NETWORK LINK																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1				41	37		132		54	37		35	41	25					
2	1				1	3		4			1					2	1		1
3	18	17				1	47				14					2			15
4	3	5		1		1					1					2	1		2
5			31						6						23	6			
6																			
7	16	16												1	16	16	16		
8	10	20						10			50						10	20	40
9	2	3						1		1	1					2	1		7
TOTAL, λ_i	50	61	31	42	38	5	179	15	60	38	67	35	41	26	39	30	29	20	65

Table A-11. Interconnection Network, Messages / Second, Long Messages

SOURCE NODE	NETWORK LINK																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1				21	19		67		28	19		18	21	13					
2	1				1	2		4			1					2	1		1
3	10	9				1	24				7					1			8
4	2	5		1		1					1					2	1		2
5			16						3						12	3			
6																			
7	8	8												1	8	8	8		
8	5	10						5			26						5	10	20
9	1	2						1		1						2	1		6
TOTAL, λ_i	27	34	16	22	20	4	91	10	31	20	35	18	21	14	20	18	16	10	37

is sent from node 3, then two separate transmissions of this message packet will be initiated from node 3.

Table A-17. Network Traffic Matrix with Ring Network Modified Data. This table provides three entries for each source-destination combination. Each entry is given in data bits/second without overhead for:

16-bit data fields

32-bit data fields

32-bit control messages

The table is similar to Table A-3.

Tables A-18, A-19 and A-20. Network Traffic Matrix with Ring Network Modified Data. These tables give the number of short, medium and long messages/second, respectively, for the data in table A-17. These tables are similar to Tables A-5, A-6, and A-7.

Tables A-21, A-22 and A-23. Ring Network Link Traffic with Modified Data. These tables contain the link traffic in messages/second (λ_i) for short, medium and long message lengths. The message traffic trom Tables A-18, A-19 and A-20 are used in conjunction with the ring network message routing given in Table A-12 to arrive at a tabulation of λ_i for each network link. These tables are similar to Tables A-13, A-14, and A-15

Table A-12. Ring Network
Node – Node Message Routing

SOURCE NODE	DESTINATION NODE								
	1	2	3	4	5	6	7	8	9
1	—	1-2	1-2-3	1-2-3-4	1-2-3-4-5	1-2-3-4-5-6	1-2-3-4-5-6-7	1-2-3-4-5-6-7-8	1-2-3-4-5-6-7-8-9
2	2-3-4-5-6-7-8-9-1	—	2-3	2-3-4	2-3-4-5	2-3-4-5-6	2-3-4-5-6-7	2-3-4-5-6-7-8	2-3-4-5-6-7-8-9
3	3-4-5-6-7-8-9-1	3-4-5-6-7-8-9-1-2	—	3-4	3-4-5	3-4-5-6	3-4-5-6-7	3-4-5-6-7-8	3-4-5-6-7-8-9
4	4-5-6-7-8-9-1	4-5-6-7-8-9-1-2	4-5-6-7-8-9-1-2-3	—	4-5	4-5-6	4-5-6-7	4-5-6-7-8	4-5-6-7-8-9
5	5-6-7-8-9-1	5-6-7-8-9-1-2	5-6-7-8-9-1-2-3	5-6-7-8-9-1-2-3-4	—	5-6	5-6-7	5-6-7-8	5-6-7-8-9
6	6-7-8-9-1	6-7-8-9-1-2	6-7-8-9-1-2-3	6-7-8-9-1-2-3-4	6-7-8-9-1-2-3-4-5	—	6-7	6-7-8	6-7-8-9
7	7-8-9-1	7-8-9-1-2	7-8-9-1-2-3	7-8-9-1-2-3-4	7-8-9-1-2-3-4-5	7-8-9-1-2-3-4-5-6	—	7-8	7-8-9
8	8-9-1	8-9-1-2	8-9-1-2-3	8-9-1-2-3-4	8-9-1-2-3-4-5	8-9-1-2-3-4-5-6	8-9-1-2-3-4-5-6-7	—	8-9
9	9-1	9-1-2	9-1-2-3	9-1-2-3-4	9-1-2-3-4-5	9-1-2-3-4-5-6	9-1-2-3-4-5-6-7	9-1-2-3-4-5-6-7-8	—

Table A-13. Ring Network, Messages / Second
Short Messages

SOURCE NODE	NETWORK LINK								
	1	2	3	4	5	6	7	8	9
1	791	718	456	375	269	189	141	73	—
2	—	9	6	5	4	3	2	1	1
3	2	—	132	130	130	126	126	98	96
4	6	4	—	16	14	12	11	9	7
5	61	61	—	—	130	119	73	73	73
6	—	—	—	—	—	—	—	—	—
7	64	64	32	32	—	—	66	66	66
8	114	95	76	57	38	19	—	133	114
9	9	8	5	4	3	2	1	—	10
TOTAL, λ_l	1047	959	707	619	588	470	420	453	367

Table A-14. Ring Network, Messages / Second
Medium Messages

SOURCE NODE	NETWORK LINK								
	1	2	3	4	5	6	7	8	9
1	402	365	233	192	138	97	72	37	—
2	—	8	6	5	4	3	2	1	1
3	1	—	66	65	65	63	63	49	48
4	3	2	—	9	8	7	6	5	4
5	31	31	—	—	66	60	37	37	37
6	—	—	—	—	—	—	—	—	—
7	32	32	16	16	—	—	33	33	33
8	60	50	40	30	20	10	—	70	60
9	8	7	5	4	3	2	1	—	9
TOTAL, λ_i	537	495	366	321	304	242	214	232	192

Table A-15. Ring Network, Messages / Second
Long Messages

SOURCE NODE	NETWORK LINK								
	1	2	3	4	5	6	7	8	9
1	206	187	120	99	71	50	37	19	—
2	—	7	6	5	4	3	2	1	1
3	1	—	29	28	28	27	27	26	25
4	2	1	—	8	7	6	5	4	3
5	16	16	—	—	34	31	19	19	19
6	—	—	—	—	—	—	—	—	—
7	16	16	8	8	—	—	17	17	17
8	30	25	20	15	10	5	—	35	30
9	7	6	5	4	3	2	1	—	8
TOTAL, λ_i	278	258	188	167	157	124	108	121	103

Table A-16. Data Fields Traffic Matrix, Fields / Second
Ring Network with Modified Data
A. 16-Bit Data Field
B. 32-Bit Data Field
C. 32-Bit Control Message

SOURCE NODE		DESTINATION NODE								
		1	2	3	4	5	6	7	8	9
1	A	—	—	1211	220	700	410	270	250	2171
	B	—	—	1480	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	10
2	A	5	—	44	—	—	—	—	—	20
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
3	A	—	—	—	—	—	—	—	—	—
	B	1493	20	—	29	—	64	—	438	20
	C	—	—	—	—	—	—	—	—	—
4	A	—	—	102	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
5	A	—	—	1934	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
6	A	—	—	—	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
7	A	—	—	—	—	1010	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
8	A	—	—	—	—	—	—	600	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
9	A	—	—	44	5	—	—	—	20	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—

Table A-17. Ring Network Traffic Matrix, Bits / Second
Modified Data
A. 16-Bit Data Field
B. 32-Bit Data Field
C. 32-Bit Control Message

SOURCE NODE		DESTINATION NODE								
		1	2	3	4	5	6	7	8	9
1	A	—	—	19376	3520	11200	6560	4320	4000	34736
	B	—	—	47360	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	2560
2	A	80	—	704	—	—	—	—	—	320
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
3	A	—	—	—	—	—	—	—	—	—
	B	47776	640	—	928	—	2048	—	14016	640
	C	—	—	—	—	—	—	—	—	—
4	A	—	—	1632	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
5	A	—	—	30944	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
6	A	—	—	—	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
7	A	—	—	—	—	—	16160	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
8	A	—	—	—	—	—	—	9600	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
9	A	—	—	704	80	—	—	—	320	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—

Table A-18. Ring Network Traffic Matrix, Messages / Second
Modified Data With Short Messages
A. 16-Bit Data Field
B. 32-Bit Data Field
C. 32-Bit Control Message

SOURCE NODE		DESTINATION NODE								
		1	2	3	4	5	6	7	8	9
1	A	—	—	37.84	6.88	21.88	12.81	8.44	7.81	67.84
	B	—	—	92.5	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	5
2	A	0.16	—	1.38	—	—	—	—	—	0.63
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
3	A	—	—	—	—	—	—	—	—	—
	B	93.31	1.25	—	1.81	—	4.00	—	27.38	1.25
	C	—	—	—	—	—	—	—	—	—
4	A	—	—	3.19	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
5	A	—	—	60.44	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
6	A	—	—	—	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
7	A	—	—	—	—	31.56	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
8	A	—	—	—	—	—	—	18.75	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
9	A	—	—	1.38	0.16	—	—	—	0.63	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—

Table A-19. Ring Network Traffic Matrix, Messages / Second
Modified Data with Medium Messages
A. 16-Bit Data Field
B. 32-Bit Data Field
C. 32-Bit Control Message

SOURCE NODE		DESTINATION NODE								
		1	2	3	4	5	6	7	8	9
1	A	—	—	18.92	3.44	10.94	6.41	4.22	3.91	33.92
	B	—	—	46.25	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	2.5
2	A	0.08	—	0.69	—	—	—	—	—	0.31
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
3	A	—	—	—	—	—	—	—	—	—
	B	46.66	0.63	—	0.91	—	2.00	—	13.69	0.63
	C	—	—	—	—	—	—	—	—	—
4	A	—	—	1.60	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
5	A	—	—	30.22	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
6	A	—	—	—	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
7	A	—	—	—	—	15.78	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
8	A	—	—	—	—	—	—	9.38	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
9	A	—	—	0.69	0.08	—	—	—	0.31	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—

Table A-20. Ring Network Traffic Matrix, Messages / Second
Modified Data with Long Messages
A. 16-Bit Data Field
B. 32-Bit Data Field
C. 32-Bit Control Message

SOURCE NODE		DESTINATION NODE								
		1	2	3	4	5	6	7	8	9
1	A	—	—	9.61	1.72	5.47	3.20	2.11	1.95	16.96
	B	—	—	23.13	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	1.25
2	A	0.04	—	0.34	—	—	—	—	—	0.16
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
3	A	—	—	—	—	—	—	—	—	—
	B	23.33	0.31	—	0.45	—	1.00	—	6.84	0.31
	C	—	—	—	—	—	—	—	—	—
4	A	—	—	0.80	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
5	A	—	—	15.11	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
6	A	—	—	—	—	—	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
7	A	—	—	—	—	7.89	—	—	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
8	A	—	—	—	—	—	—	4.69	—	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—
9	A	—	—	0.34	0.04	—	—	—	0.16	—
	B	—	—	—	—	—	—	—	—	—
	C	—	—	—	—	—	—	—	—	—

Table A-21. Ring Network, Messages / Second
Modified Data with Short Messages

SOURCE NODE	NETWORK LINK								
	1	2	3	4	5	6	7	8	9
1	263	263	132	125	103	90	81	73	—
2	—	4	2	2	2	2	2	2	1
3	—	—	132	130	130	126	126	98	96
4	4	4	—	4	4	4	4	4	4
5	61	61	—	—	61	61	61	61	61
6	—	—	—	—	—	—	—	—	—
7	32	32	32	32	—	—	32	32	32
8	19	19	19	19	19	19	—	19	19
9	4	4	2	1	1	1	1	—	4
TOTAL, λ_i	385	387	319	313	320	303	307	289	217

Table A-22. Ring Network, Messages / Second
Modified Data with Medium Messages

SOURCE NODE	NETWORK LINK								
	1	2	3	4	5	6	7	8	9
1	134	134	68	64	53	46	41	37	—
2	—	3	2	2	2	2	2	2	1
3	1	—	66	65	65	63	63	49	48
4	2	2	—	2	2	2	2	2	2
5	31	31	—	—	31	31	31	31	31
6	—	—	—	—	—	—	—	—	—
7	16	16	16	16	—	—	16	16	16
8	10	10	10	10	10	10	—	10	10
9	3	3	2	1	1	1	1	—	3
TOTAL, λ_i	197	199	164	160	164	155	156	147	111

Table A-23. Ring Network, Messages / Second
Modified Data with Long Messages

SOURCE NODE	NETWORK LINK								
	1	2	3	4	5	6	7	8	9
1	70	70	36	34	28	24	21	19	—
2	—	3	2	2	2	2	2	2	1
3	1	—	35	34	34	33	26	26	25
4	1	1	—	1	1	1	1	1	1
5	16	16	—	—	16	16	16	16	16
6	—	—	—	—	—	—	—	—	—
7	8	8	8	8	—	—	8	8	8
8	5	5	5	5	5	5	—	5	5
9	3	3	2	1	1	1	1	—	3
TOTAL, λ_l	104	106	88	85	87	82	75	77	59

A.3 Global Bus Network Tables

Table A-24. Global Bus Network Node-Node Message Routing. This table shows the route each message takes as it goes from a source node to a destination node. For example, location (6,8) contains the entry (6-8) indicating a direct routing from the source node to the destination node.

Table A-25. Global Bus Network Link Traffic. This table contains the link traffic in messages/second (λ_i) for short, medium and long message lengths. The message traffic data from Tables A-5, A-6, and A-7 are used in conjunction with the global bus network message routing given in Table A-24 to arrive at a tabulation of λ for the network link.

Note: The data traffic flow in these tables is designed such that if the same message is required at both nodes 5 and 6 and is sent from node 3, then two separate transmissions of this message will be initiated from node 3.

Table A-26 Global Bus Network Link Traffic with Modified Data. This table contains the link traffic in messages/second (λ) for short, medium and long message lengths. These tables are similar to Tables A-21, A-22, and A-23.

Note: The data traffic flow in Table A-26 reflects a reduction in the traffic to take advantage of the global bus network features. For example, if a message is required at both nodes 5 and 6 and is sent from node 3, then only one transmission of this message will be initiated from node 3.

Table A-27 Global Bus Network. Messages Received at Node. This table contains the short, medium and long messages received at each node.

Table A-24. Global Bus Network
Node–Node Message Routing

SOURCE NODE	DESTINATION NODE								
	1	2	3	4	5	6	7	8	9
1	—	1-2	1-3	1-4	1-5	1-6	1-7	1-8	1-9
2	2-1	—	2-3	2-4	2-5	2-6	2-7	2-8	2-9
3	3-1	3-2	—	3-4	3-5	3-6	3-7	3-8	3-9
4	4-1	4-2	4-3	—	4-5	4-6	4-7	4-8	4-9
5	5-1	5-2	5-3	5-4	—	5-6	5-7	5-8	5-9
6	6-1	6-2	6-3	6-4	6-5	—	6-7	6-8	6-9
7	7-1	7-2	7-3	7-4	7-5	7-6	—	7-8	7-9
8	8-1	8-2	8-3	8-4	8-5	8-6	8-7	—	8-9
9	9-1	9-2	9-3	9-4	9-5	9-6	9-7	9-8	—

Table A-25. Global Bus Network, Messages / Second

SOURCE NODE	MESSAGE LENGTH		
	SHORT	MEDIUM	LONG
1	3012	1536	995
2	31	30	29
3	840	420	191
4	79	44	36
5	590	299	154
6	0	0	0
7	390	195	99
8	646	340	170
9	42	39	36
TOTAL, λ	5630	2903	1710

Table A-26. Global Bus Network, Messages / Second Modified Data

SOURCE NODE	MESSAGE LENGTH		
	SHORT	MEDIUM	LONG
1	263	134	70
2	4	3	3
3	132	66	35
4	4	2	1
5	61	31	16
6	0	0	0
7	32	16	8
8	19	10	5
9	4	3	3
TOTAL, λ	519	265	141

Table A-27. Global Bus Network, Messages / Second
Messages Received at Node

RECEIVING NODE	MESSAGE LENGTH		
	SHORT	MEDIUM	LONG
1	95	48	25
2	2	1	1
3	200	101	53
4	10	6	4
5	54	27	14
6	17	9	5
7	28	15	8
8	37	19	12
9	76	39	21

APPENDIX B

ILLUSTRATIVE EXAMPLES

B.0 Average Message Traffic Illustrative Examples

The total average message traffic through each of the links is

$$\lambda = \sum_i \lambda_i$$

The value of short messages for the interconnection network topology is

$$\lambda = 97 + 117 + 61 + 82 + 74 + 8 + 356 + 24 + 118 + 74 + 127 + 68 + 80 + 50 + 78 + 54 + 54 + 38 + 119$$

$$\lambda = 1679 \text{ messages/second}$$

The total average message traffic using short messages for the network topology is

$$\lambda = 1047 + 959 + 707 + 619 + 588 + 470 + 420 + 453 + 367$$

$$\lambda = 5630 \text{ message/second}$$

B.1 Average Message Delay Illustrative Example

An example of a solution for the average message delay, T, is given for an inter-connection network using short message lenghts.

The total incoming message rate, γ, for the network is defined as

$$\gamma = \sum_{jk} \gamma_{jk}$$

γ = 68 + 5 + 164 + 93 + 5 + 76 + 5 + 101 + 5 + 75 + 5 + 43 + 5 + 63 + 5 + 68 + 5 + 1 + 3 + 1 + 1 + 1 + 1 + 1 + 0 + 94 + 2 + 2 + 4 + 28 + 2 + 1 + 2 + 4 + 2 + 2 + 1 + 2 + 2 + 12 + 61 + 11 + 46 + 2 + 32 + 32 + 19 + 19 + 19 + 19 + 19 + 19 + 19 + 1 + 1 + 3 + 1 + 1 + 1 + 1 + 1 = 1287 messages/second

Using equation (4-4) and substituting the following is obtained

$$T_i = \frac{1}{\mu C_i - \lambda i}$$

$$T_1 = \frac{1}{\frac{291839}{576} - 97}$$

T_1 = 0.002441 seconds

In a similar manner the T_i values are obtained for the other links.

T_2 = 0.002223

T_3 = 0.003078

T_4 = 0.002655

T_5 = 0.002795

T_6 = 0.008500

T_7 = 0.001274

T_{11} = 0.002133

T_{12} = 0.002915

T_{13} = 0.002688

T_{14} = 0.003400

T_{15} = 0.002722

T_{16} = 0.003272

$T_8 = 0.004907$

$T_9 = 0.002213$

$T_{10} = 0.002795$

$T_{17} = 0.003272$

$T_{18} = 0.003900$

$T_{19} = 0.002204$

The average message delay, T, for the network can now be determined using equation (4-5) revised slightly

$$T = \frac{1}{\gamma} \sum_i \lambda_i T_i$$

$$T = \frac{1}{1287} \Big[97 \times 0.002441 + 117 \times 0.002223 + 61 \times 0.003078 + 82 \times 0.002655 + 74 \times 0.002795 + 8 \times 0.008500 + 356 \times 0.001274 + 24 \times 0.004907 + 118 \times 0.002213 + 74 \times 0.002795 + 127 \times 0.002133 + 68 \times 0.002915 + 80 \times 0.002688 + 50 \times 0.003400 + 78 \times 0.002722 + 54 \times 0.003272 + 54 \times 0.003272 + 38 \times 0.003900 + 119 \times 0.002204 \Big]$$

$T = 0.003144$ seconds/message

B.2 Capacity Allocation Illustration Examples

The equal assignment, proportional assignment, and optimum assignment capacity computation are shown in the following paragraphs.

B.2.1 Equal Capacity Assignment Strategy

A network containing nine links and a total capacity of five megabits/ second has a capacity of each link of

$$C_i = C/M$$

$$C_i = \frac{5x10^6}{9}$$

$$C_i = 555{,}556 \text{ bits/second}$$

B.2.2 Proportional Capacity Assignment Strategy

The capacity of each link is solved using the equation

$$C_i|prop = \frac{C\,\lambda_i}{\lambda}$$

The capacity for link 1 of the ring network is

$$C_i|prop = \frac{5x10^6 x\ 1047}{5630}$$

$$C_i|prop = 929{,}840 \text{ bits/second}$$

B.2.3 Optimum Capcity Assignment Strategy

The optimum capacity assignment for each link is found by using

$$C_i|opt = \frac{\lambda_i}{\mu_i} + \frac{C(1-\rho)\sqrt{\lambda_i/\mu_i}}{\sum_j \sqrt{\lambda_j/\mu_j}}$$

An example follows for the interconnection network using short messages.

The traffic intensity parameter for this case is

$$\rho = \frac{\lambda}{\mu C}$$

$$\rho = \frac{1679 \times 576}{5 \times 10^6}$$

$$\rho = 0.1934$$

Square root values are then determined as follows:

$$\sum_j \lambda_j/\mu_j = \sqrt{97 \times 576} + \sqrt{117 \times 576} + \sqrt{61 \times 576} + \sqrt{74 \times 576} +$$

$$\sqrt{8 \times 576} + \sqrt{356 \times 576} + \sqrt{24 \times 576} + \sqrt{118 \times 576} +$$

$$\sqrt{74 \times 576} + \sqrt{127 \times 576} + \sqrt{68 \times 576} + \sqrt{80 \times 576} +$$

$$+ \sqrt{50 \times 576} + \sqrt{78 \times 576} + \sqrt{54 \times 576} + \sqrt{54 \times 576} +$$

$$+ \sqrt{38 \times 576} + \sqrt{119 \times 576}$$

$$= 236.37 + 259.60 + 187.45 + 217.33 + 206.46 + 67.88 +$$

$$452.83 + 117.58 + 260.71 + 206.46 + 270.47 + 197.91 +$$

$$214.66 + 169.71 + 211.96 + 176.36 + 176.36 + 147.95 +$$

$$261.81$$

$$= 4039.86$$

Substituting in the optimum expression

$$C_1|\text{opt} = 97 \times 576 + \frac{5 \times 10^6 (1-0.1934)\ 236.37}{4039.86}$$

$$= 291839 \text{ bits/second}$$

Similarly, the $C_i|opt$ values are found for the remaining links of the interconnection network.

$C_2|opt$ = 326546 bits/second	$C_{11}|opt$ = 343154 bits/second
$C_3|opt$ = 222260 bits/second	$C_{12}|opt$ = 236737 bits/second
$C_4|opt$ = 264188 bits/second	$C_{13}|opt$ = 260374 bits/second
$C_5|opt$ = 248725 bits/second	$C_{14}|opt$ = 298214 bits/second
$C_6|opt$ = 72374 bits/second	$C_{15}|opt$ = 207164 bits/second
$C_7|opt$ = 757110 bits/second	$C_{16}|opt$ = 207164 bits/second
$C_8|opt$ = 131198 bits/second	$C_{17}|opt$ = 207164 bits/second
$C_9|opt$ = 248725 bits/second	$C_{18}|opt$ = 169580 bits/second
$C_{10}|opt$ = 248725 bits/second	$C_{19}|opt$ = 329904 bits/second

APPENDIC C

ANALYSIS RESULTS

C.0 General Tables

Table C-1. Average Message Delay, Seconds/Message, Equal Capacity Assignment Strategy with Short Messages. This table provides a tabulation of message delays by network bandwidth and network topology.

Table C-2. Average Message Delay, Seconds/Message, Equal Capacity Assignment Strategy with Medium Messages. Message delays in this table are given by network topology and network bandwidth.

Table C-3. Average Message Delay, Seconds/Message, Equal Capacity Assignment Strategy with Long Messages. A tabulation of message delays by network bandwidth and network topology is provided in this table.

Table C-4. Average Message Delay, Seconds/Message, Proportional Capacity Assignment Strategy with Short Messages. This table provides a tabulation of message delays by network bandwidth and network topology.

Table C-5. Average Message Delay, Seconds/Message, Proportional Capacity Assignment with Medium Messages. Messages delays in this table are given by network topology and network bandwidth.

Table C-6. Average Message Delay, Seconds/Message Proportional Capacity Assignment with Long Messsges. A tabulation of message delays by network bandwidth and network topology is provided in this table.

Table C-7. Average Messge Delay, Seconds/Message, Optimum Capacity Assignment Strategy with Short Messages. This table provides a tabulation of message delays by network bandwidth and network topology.

Table C-8. Average Message Delay, Seconds/Message, Optimum Capacity Assignment Strategy with Medium Messages. Message delays in this table are given by network topology and network bandwidth.

Table C-9. Average Message Delay, Seconds/Message, Optimum Capacity Assignment Strategy with Long Messages. A tabulation of message delays by network bandwidth and network topology is provided in this table.

Table C-1. Average Message Delay, Seconds / Message (T)
Equal Capacity Assignment Strategy
With Short Messages

NETWORK BANDWIDTH, MEGABITS	NETWORK TOPOLOGY				
	INTER-CONNECTION	RING	GLOBAL BUS	RING (MODIFIED DATA)	GLOBAL BUS (MODIFIED DATA)
1	.003772[1]	−.011025	−.001123	−.056081	.000822
2	.010326[1]	−.012514	−.002027	.351756[1]	.000339
3	.002272[1]	−.059494	−.010374	.022112	.000213
4	.032868	.011161	.003328	.012323	.000156
5	.005545	.132716	.001434	.008572	.000123
10	.001742	.003735	.000373	.003410	.000059
20	.000779	.001397	.000150	.001548	.000029

NOTE: 1. T VALUES INCLUDE NEGATIVE T_i VALUES.

Table C-2. Average Message Delay, Seconds / Message (T)
Equal Capacity Assignment Strategy With Medium Messages

NETWORK BANDWIDTH, MEGABITS	NETWORK TOPOLOGY				
	INTER-CONNECTION	RING	GLOBAL BUS	RING (MODIFIED DATA)	GLOBAL BUS (MODIFIED DATA)
1	-.024185	-.021749	-.002207	-.127564	.001529
2	.019284[1]	-.048891	-.004112	.328306	.000636
3	.002786[1]	.159854[1]	-.030063	.040013	.000401
4	.025761	.015150	.005661	.022760	.000293
5	.009648	.030293	.002587	.015952	.000231
10	.003272	.006925	.000696	.006410	.000112
20	.001475	.002624	.000283	.002921	.000055

NOTE: 1. T VALUES INCLUDE NEGATIVE T_I VALUES.

Table C-3. Average Message Delay, Seconds / Message (T)
Equal Capacity Assignment Strategy With Long Messages

NETWORK BANDWIDTH, MEGABITS	NETWORK TOPOLOGY				
	INTER-CONNECTION	RING	GLOBAL BUS	RING (MODIFIED DATA)	GLOBAL BUS (MODIFIED DATA)
1	.019857[1]	-.040977	-.003951	-.214031	.003008
2	.041680[1]	-.051378	-.006403	-.186083	.001241
3	.005835[1]	.489296[1]	-.016873	.079216	.000782
4	.044311	.029779	.026562	.044341	.000571
5	.018462	.118106	.007432	.030907	.000449
10	.006393	.013252	.001615	.012334	.000218
20	.002888	.005006	.000630	.005607	.000107

NOTE: 1. T VALUES INCLUDE NEGATIVE T_i VALUES.

Table C-4. Average Message Delay, Seconds / Message (T)
Proportional Capacity Assignment Strategy With Short Messages

NETWORK BANDWIDTH, MEGABITS	NETWORK TOPOLOGY				
	INTER-CONNECTION	RING	GLOBAL BUS	RING (MODIFIED DATA)	GLOBAL BUS (MODIFIED DATA)
1	.434020	-.010111	—	-.044614	—
2	.013823	-.018246	—	.077898	—
3	.007023	.093368	—	.020794	—
4	.004708	.029952	—	.011999	—
5	.003540	.012906	—	.008432	—
10	.001581	.003356	—	.003392	—
20	.000750	.001353	—	.001545	—

NOTE: 1. T VALUES INCLUDE NEGATIVE T_i VALUES.

Table C-5. Average Message Delay, Seconds / Message (T)
Proportional Capacity Assignment Strategy With Medium Messages

NETWORK BANDWIDTH, MEGABITS	NETWORK TOPOLOGY				
	INTER-CONNECTION	RING	GLOBAL BUS	RING (MODIFIED DATA)	GLOBAL BUS (MODIFIED DATA)
1	.518750	-.019864	—	.092430	—
2	.025806	-.037010	—	.128096	—
3	.013232	-.270561	—	.037833	—
4	.008897	.050949	—	.022194	—
5	.006702	.023282	—	.015703	—
10	.003000	.006267	—	.006377	—
20	.001425	.002546	—	.002915	—

NOTE: 1. T VALUES INCLUDE NEGATIVE T_i VALUES.

Table C-6. Average Message Delay, Seconds / Message (T)
Proportional Capacity Assignment Strategy With Long Messages

NETWORK BANDWIDTH, MEGABITS	NETWORK TOPOLOGY				
	INTER-CONNECTION	RING	GLOBAL BUS	RING (MODIFIED DATA)	GLOBAL BUS (MODIFIED DATA)
1	2.65574	-.035561	—	-.168219	—
2	.052153	-.057627	—	.264729	—
3	.026335	-.151863	—	.074077	—
4	.017615	.239055	—	.043063	—
5	.013233	.066885	—	.030355	—
10	.005898	.014537	—	.012262	—
20	.002797	.005667	—	.005594	—

NOTE: 1. T VALUES INCLUDE NEGATIVE T_i VALUES.

Table C-7. Average Message Delay, Seconds / Message (T) Optimum Capacity Assignment Strategy With Short Messages

NETWORK BANDWIDTH, MEGABITS	NETWORK TOPOLOGY				
	INTER-CONNECTION	RING	GLOBAL BUS	RING (MODIFIED DATA)	GLOBAL BUS (MODIFIED DATA)
1	.385489	-.009804	—	-.044345	—
2	.012277	-.017692	—	.077429	—
3	.006237	-.090535	—	.020670	—
4	.004181	.029043	—	.011927	—
5	.003144	.012514	—	.008382	—
10	.001404	.003254	—	.003371	—
20	.000666	.001312	—	.001535	—

NOTE: 1. T VALUES INCLUDE NEGATIVE T_i VALUES.

Table C-8. Average Message Delay, Seconds / Message (T) Optimum Capacity Assignment Strategy With Medium Messages

NETWORK BANDWIDTH, MEGABITS	NETWORK TOPOLOGY				
	INTER-CONNECTION	RING	GLOBAL BUS	RING (MODIFIED DATA)	GLOBAL BUS (MODIFIED DATA)
1	.464553	−.019264	—	−.091864	—
2	.023110	−.035892	—	.127311	—
3	.011850	−.262390	—	.037600	—
4	.007968	.049409	—	.022058	—
5	.006002	.022579	—	.015607	—
10	.002687	.006078	—	.006338	—
20	.001277	.002469	—	.002897	—

NOTE: 1. T VALUES INCLUDE NEGATIVE T_i VALUES.

Table C-9. Average Message Delay, Seconds / Message (T) Optimum Capacity Assignment Strategy With Long Messages

NETWORK BANDWIDTH, MEGABITS	NETWORK TOPOLOGY				
	INTER-CONNECTION	RING	GLOBAL BUS	RING (MODIFIED DATA)	GLOBAL BUS (MODIFIED DATA)
1	2.40618	-.030334	—	-.167108	—
2	.047253	-.049156	—	.262980	—
3	.023861	-.129540	—	.073587	—
4	.015960	.203915	—	.042779	—
5	.011990	.057053	—	.030154	—
10	.005344	.012400	—	.012180	—
20	.002534	.004834	—	.005557	—

NOTE: 1. T VALUES INCLUDE NEGATIVE T_i VALUES.

APPENDIX D

SIMULATION RESULTS

D.0 General Tables

Table D-1. Node Instructions per cycle. This table provides a tabulation of the number of instructions per cycle for each node is the global bus network (Burke 1980).

Table D-2. Node Processing Times, Seconds. The number of instructions executed per cycle divided by the processing capability in million instructions per second results in the node processing times presented in this table.

Table D-3. Global Bus Network Simulation, Mean Message delay, μ seconds, using RN1 Random Number Seed. Data from thirty-six runs are presented including overall mean delay, two-, three-, and four-node mean delays.

Table D-4. Random Number Seeds. The random number seeds included in each set are shown in this table.

Table D-5. Global Bus Network Simulation, Mean Message Delay, μ seconds. The results from five runs, each with a different random number set, are given for each run number case.

Table D-1. Node Instruction Per Cycle

NODE	NUMBER OF INSTRUCTIONS PER CYCLE
1. SENSOR DATA PROCESSOR	42710
2. TARGET MOTION ANALYSIS	65860
3. DATA BASE CONTROLLER	21790
4. TIME BEARING	33260
5. WEAPONS COMMUNICATIONS CONTROLLER	33200
6. OPERATIONS SUMMARY	37700
7. WEAPONS PRESET	31780
8. GEOGRAPHIC	34740
9. TARGET MOTION ANALYSIS	65860

Table D-2. Node Processing Times, Seconds

NODE	PROCESSOR CAPACITY, MIPS		
	0.2	0.4	0.6
1. SENSOR DATA PROCESSOR	0.2136	0.1068	0.0712
2. TARGET MOTION ANALYSIS	0.3293	0.1647	0.1098
3. DATA BASE CONTROLLER	0.1090	0.0545	0.0363
4. TIME BEARING	0.1663	0.0832	0.0554
5. WEAPONS COMMUNICATIONS CONTROLLER	0.1660	0.0830	0.0553
6. OPERATIONS SUMMARY	0.1885	0.0943	0.0628
7. WEAPONS PRESET	0.1589	0.0795	0.0530
8. GEOGRAPHIC	0.1737	0.0869	0.0579
9. TARGET MOTION ANALYSIS	0.3293	0.1647	0.1098

Table D-3. Global Bus Network Simulation
Mean Message Delay, μ Seconds
Using RN1 Random Number Seed

RUN	OVERALL MEAN	TWO-NODE MEAN	THREE-NODE MEAN	FOUR-NODE MEAN
0512	5117	4693	8924	9933
0514	2396	2180	4120	4761
0516	1595	1445	2752	3355
0522	5146	4748	8701	9899
0524	2404	2195	4178	4838
0526	1619	1461	2794	3502
0532	5062	4625	9067	9641
0534	2332	2134	3919	4496
0536	1523	1400	2541	3050
0542	5039	4597	9152	9720
0544	2324	2130	3876	4481
0546	1518	1398	2510	3013
1012	5893	5345	10818	12174
1014	3093	2743	5804	6870
1016	2261	1963	4461	5123
1022	5325	4841	9065	11025
1024	2615	2362	4866	5558
1026	1777	1593	3628	3833
1032	5250	4754	8904	10231
1034	2442	2223	4480	5105
1036	1647	1476	2988	3480
1042	5145	4747	8700	9899
1044	2401	2191	4178	4838
1046	1614	1457	2794	3499

Table D-3. Global Bus Network Simulation (Cont.)
Mean Message Delay, μ Seconds
Using RN1 Random Number Seed

RUN	OVERALL MEAN	TWO-NODE MEAN	THREE-NODE MEAN	FOUR-NODE MEAN
2012	8734	7946	13038	17867
2014	5797	5198	11442	12442
2016	4278	3825	7962	10024
2022	5893	5345	10818	12174
2024	3093	2743	5804	6870
2026	2261	1963	4461	5123
2032	5598	5125	9396	11699
2034	2753	2483	5457	5735
2036	1949	1743	3978	4114
2042	5325	4841	9065	11025
2044	2615	2362	4866	5558
2046	1777	1593	3628	3833

Table D-4. Random Number Seeds

SET NUMBER	SEEDS		
01	03	07	03
02	05	08	04
03	01	03	06
04	03	07	05
05	01	01	01

Table D-5. Global Bus Network Simulation
Mean Message Delay, μ Seconds

RUN NUMBER	MESSAGE PATH, NODES	RANDOM NUMBER SET				
		01	02	03	04	05
0516	OVERALL	1602	1609	1637	1609	1595
	TWO	1443	1442	1449	1442	1445
	THREE	2733	2903	2708	2903	2752
	FOUR	3278	3312	3376	3312	3355
0536	OVERALL	1521	1524	1553	1524	1523
	TWO	1379	1382	1382	1382	1400
	THREE	2531	2531	2535	2531	2541
	FOUR	3016	3029	3044	3029	3050
0546	OVERALL	1517	1519	1533	1519	1518
	TWO	1377	1380	1378	1380	1398
	THREE	2508	2507	2506	2507	2510
	FOUR	2988	2982	3004	2982	3013
1036	OVERALL	1668	1667	1697	1667	1647
	TWO	1484	1483	1483	1483	1476
	THREE	2950	2864	2981	2864	2988
	FOUR	3626	3625	3600	3625	3480
1046	OVERALL	1641	1626	1667	1626	1614
	TWO	1471	1455	1464	1455	1457
	THREE	2871	2858	2806	2858	2794
	FOUR	3412	3411	3461	3411	3499

D.1 Figures

Figure D-1. Global Bus Network Simulation, Overall Mean Message delay, μ seconds, using RN1 Random Number Seed. The message delay is plotted for each run in the 50 millisecond message arrival interval series.

Figure D-2. Global Bus Network Simulation, Overall mean Message Delay, μ seconds, using RN1 Randon Number Seed. The message delay is plotted for each run in the 100 millisecond message arrival interval series.

Figure D-3. Global Bus Network Simulation Overall Mean Message Delay, μ seconds, using RN1 Random Number Seed. The message delay is plotted for each run in the 200 millisecond message arrival interval series.

D.2 Mean, Variance and 90% Confidence Interval Illustrative Example (Gordon 1969)

p = repetitions

n = sample size

Mean:

Figure D-1. Global Bus Network Simulation
Overall Mean Message Delay, μ Seconds
Using RN1 Random Number Seed
05 Run Series

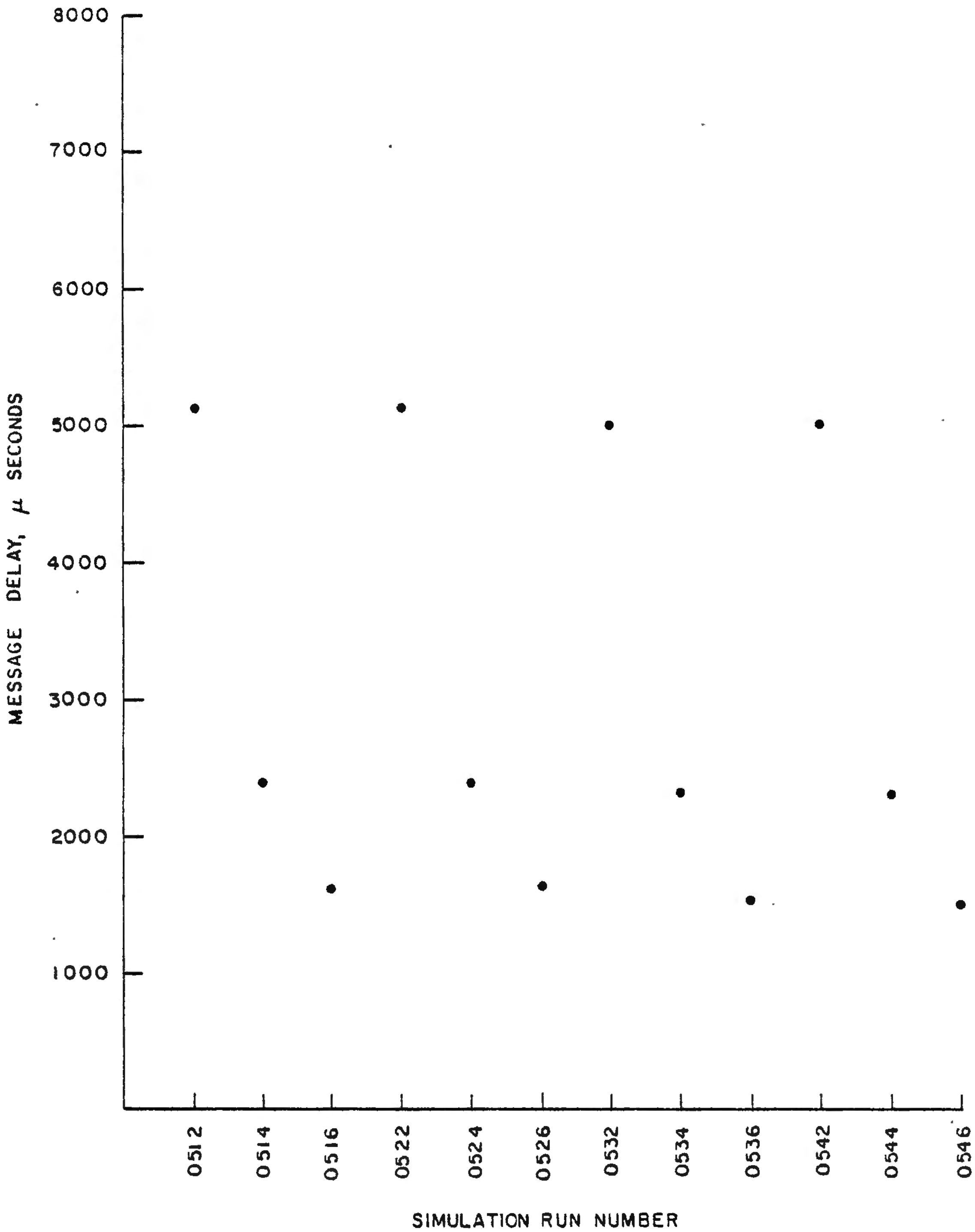
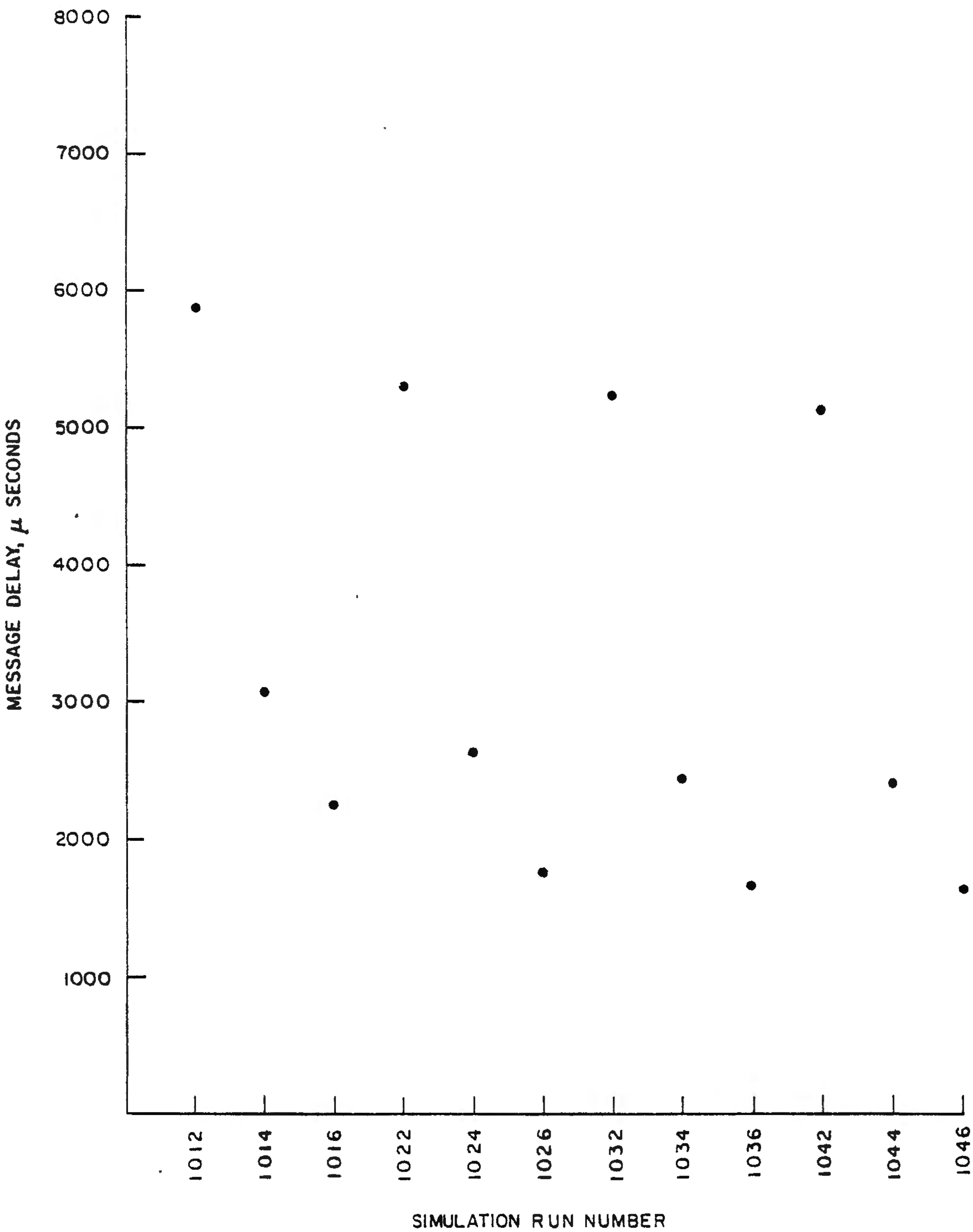


Figure D-2. Global Bus Network Simulation
Overall Mean Message Delay, μ Seconds
Using RN1 Random Number Seed
10 Run Series



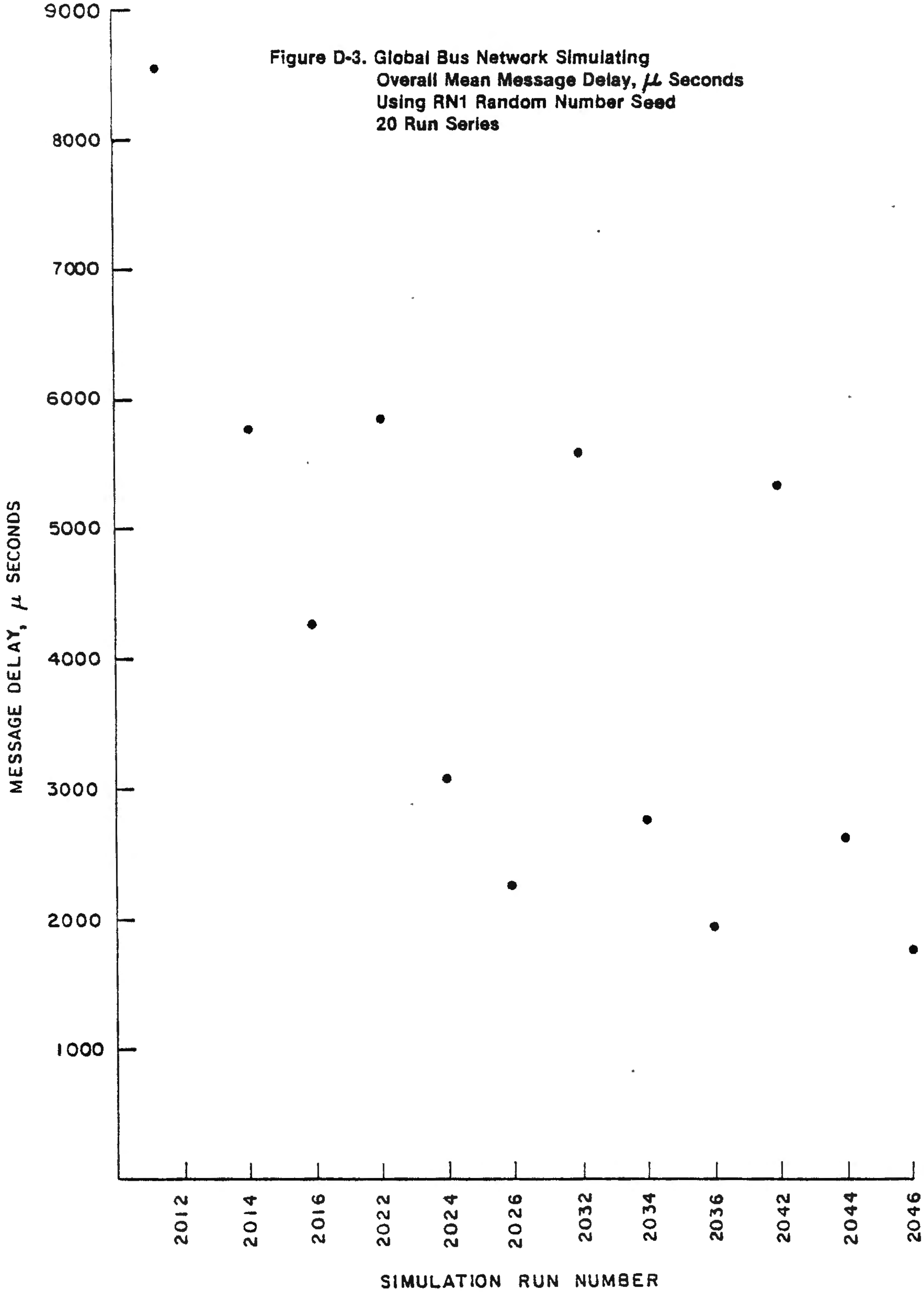


Figure D-3. Global Bus Network Simulating
Overall Mean Message Delay, μ Seconds
Using RN1 Random Number Seed
20 Run Series

$$m(n) = \frac{1}{p} \sum_{j=1}^{p} \bar{x}_j(n)$$

$$m(1000) = \frac{1}{5} \sum_{j=1}^{5} \bar{x}_j(1000)$$

$$= \frac{1}{5} \left[1602+1609+1637+1609+1595\right]$$

$$= 1610$$

Variance

$$s^2(n) = \frac{1}{p-1} \sum_{j=1}^{p} \left[\bar{x}_j(n)-m(n)\right]^2$$

$$s^2(1000) = \frac{1}{5-1} \sum_{j=1}^{5} \left[\bar{x}_j(1000)-m(1000)\right]^2$$

$$= \frac{1}{4} \Big[(1602-1610)^2+(1609-1610)^2(1637-1610)^2+(1609-1610)^2$$

$$+ (1595-1610)^2\Big]$$

$$= 255$$

Confidence Interval:

$$\bar{x} \pm \frac{s}{\sqrt{n}} \mu_{\gamma/2}$$

$$\bar{x} \pm \frac{15.97}{\sqrt{5}} \times 2.132$$

$$1610 \pm 15.227$$

BIBLIOGRAPHY OF COMPLETE THESIS

George A. Anderson and E. Douglas Jensen,"Computer Interconnection Structures: Taxonomy, Characteristics, and Examples," ACM Computing Surveys, Vol. 7, No. 4, December 1975.

Vijoy Ashuja,"On Congestion Problems in Communication Networks," Trend and Applications: 1978 Distributed Processing, IEEE Computer Society, Long Beach, CA 90803, May 1978.

Olin H. Bray,"Distributed Database Design Consideration," Trends and Application 1976: Computer Networks, IEEE Computer Society, Long Beach, CA 90802, November 1976.

G. A. Champine, Six Approaches to Distributed Data Bases, Datamation, Technical Publishing Company, Greenwich, CT 06830, May 1977.

R. F. Effertz, R. I. Fox and F. R. Hultberg,"Computers for a Distributing Processing System," Proceedings Trends and Application: 1979, IEEE Computer Society, Long Beach, CA 90803, May 1979.

Honey S. Elovitz and Constance L. Heitmeyer,"What is a Computer Network?" Computer Networks: A Tutorial, IEEE Computer Society, Long Beach, CA 90803, 1978 Revised and Updated Edition.

David J. Farber, Networks: An Introduction, Datamation, Technical Publishing Company, Greenwich, CT 06830, April 1972.

David J. Farber et al,"The Distributed Computing System," IEEE Compcon 73 Proceedings, March 1973.

Geoffrey Gordon, System Simulation,Prentice-Hall, Englewood Cliffs, NJ, 1969.

J.R. Jackson,"Networks of Waiting Lines," Operations Research, 5 (1957).

J. Jafari, J. Spragins and T. Lewis,"A New Modular Loop Architecture for Distributed Computer Systems," Trends and Applications: 1978 Distributing Processing, IEEE Computer Society, Long Beach, CA 90803, May 1978.

E. Douglas Jensen,"The Honeywell Experimental Distributed Processor-An Overview," Computer, IEEE Computer Society, Long Beach, CA 90803, January 1978.

Leonard Kleinrock, Queuing Systems, 2 Vols., John Wiley and Sons, Inc., New York, New York, 1976.

Leonard Kleinrock,"On Communications and Networks," IEEE Transactions on Computers, Vol. C-25, No. 12, December 1976.

Richard C. Kuhns and Marc C. Shoquist,"A Serial Data Bus System for Local Processing Networks," Digest of Papers, Compcon Spring 1979, IEEE Computer Society, Long Beach, CA 90803, March, 1979.

Lawrence L. Lapin, Statistics Meaning and Method, Harcourt Brace Jovanovich, New York, 1975.

Ming T. Liu, Roberto Pardo and Gojko Babic, "A Performance Study of Distributed Control Loop Network," Proceedings of the 1977 International Conference on Parallel Processing, IEEE Computer Society, Long Beach, CA 90803, August 1977.

R. Mauriello, L. Bloom, and R.J. Malinzak,"A Distributed Processing System," Proceedings Trends and Application: 1979, IEEE Computer Society, Long Beach, CA 90803, May 1979.

John M. McQuillan and Vinton G. Cerf, Tutorial: A Practical View of Computer Communications Protocols, IEEE Computer Society, Long Beach, CA 90803, 1978.

E. T. Nakahara and R. Mauriello, "Data Bus Communications for a Distributed Processing System," Proceedings Trends and Application: 1979, IEEE Computer Society, Long Beach, CA 90803, May 1979.

R. L. Pickholtz and M. Schwartz, NSF Symposium on Modeling and Analysis of Data Networks: A Report, National Science Foundation, Washington, D.C., March 1976.

Mischa Schwartz, Computer-Communication Network Design and Analysis, Prentice-Hall, Inc., Englewood Cliffs, New Jersey 07632, 1977.

Kenneth M. Zemrowski, "Problems of Data Base Use in a Distributed Data Network," Fifteenth Annual Technical Symposium, ACM, 1976.

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